An Analysis of Market Structure:
The Nickel Industry

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NOTE:

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EXECUTIVE SUMMARY

This research analyzes theoretically and empirically the pricing and production policies of the Canadian nickel industry from the 1930's to the early 1980's. During this period the world nickel market evolved from an industry dominanted by a single firm, the International Nickel Company (Inco) of Canada, through a relatively lengthy period during which Inco acted as a price leader and faced increasing competition from other firms, to a market structure that can be described as very competitive. An important objective of this research then, is to determine if a pricing policy followed by a dominant firm in a mineral resource industry which encourages entry by other firms, with its resulting impact on market share, can be optimal from the firm's long-run point of view.

To this end, a general model of a nonrenewable natural resource industry is developed. It is assumed that the industry is dominanted by a single firm that is confronted with potential entry and expansion from a group of smaller, price taking firms. The dominant firm sets the market price of the resource and, allowing the smaller firms to supply as much of the resource as they desire, provides for the residual demand in the market. Further, capital adjustment constraints are incorporated into the model; these constraints prevent the smaller firms in the industry from quickly increasing the level of their capital stocks.

The major conclusion derived from the theoretical model implies that if the constraints faced by the smaller, fringe firms are sufficiently binding, then it is expected that the market share of the

dominant firm will be decreasing over time. That is, it can be optimal for the dominant firm to set a price for the resource that encourages a high level of entry into the industry, even though this implies a more competitive industry in the future and a loss in market power for the dominant firm. This result is important because previous models predict a nonrenewable resource industry will become more monopolistic over time. The nickel industry, however, has experienced the exact opposite trend in market structure. The present model then, by considering the effect of capital adjustment constraints, more accurately explains the observed history of the nickel industry.

A second conclusion of this study suggests that the market price of a resource will, in general, change at a rate that is not equal to the market rate of interest. Previous analysis has concluded that the net price of a nonrenewable resource, market price less marginal production costs, will increase at a rate equal to the interest rate. Empirical studies of various resource industries, however, have failed to verify such a relationship. The present research points out that these results are most likely due to the nonavailablity of adequate cost data, which are essential for obtaining reliable results. Many empirical studies consider only market prices, not net prices, which the present study implies will not show the expected relationship with the interest rate if costs are changing over time, if capacity adjustment constraints exist, or if the user cost of the resource is small relative to marginal production costs. Further, the present model also concludes that when capacity adjustment con-

straints are binding, net resource prices will be increasing at a rate less than the market interest rate, and may even be decreasing. Examination of nickel prices implies virtually no relationship between their rate of change and the interest rate.

This study includes an overview of the nickel industry and empirical analysis of the available nickel data concerning costs, prices, and market shares. The history of the nickel industry presented in this report is not intended to be all inclusive but instead focuses on the problems faced by nickel producers in developing a nickel deposit. The factors that have hindered development can be divided into three catagories; those concerned with the development of the mining facility itself and the related infrastructure, those associated with the procurement of a suitable refining process, and those related to the delivery of the finished nickel to the market. The development of several major nickel deposits are documented in order to illustrate these difficulties. All in all, these factors have led to a development period of between five to fifteen years for most nickel deposits. The constraints on increasing capital stocks quickly as suggested by the theoretical analysis are appropriate then for the nickel industry, in the sense that an assumption of instantaneous, or even reasonably quick, capital adjustments would not be very realistic.

The theoretical model developed concludes that, given capital adjustment constraints, the market structure of the industry is expected to evolve over time towards competition. A pricing policy followed by the dominant firm that encourages entry into the industry

and leads to a declining market share for the dominant firm can be optimal. That the nickel industry has undergone such a change is quite obvious, as evidenced by the market share data for the industry. Empirical analysis of the data shows that Canada has lost its market share in the industry at an increasing rate, suggesting that the capital adjustment constraints were overcome to a great extent by the later part of the time period considered.

The results of analyzing nickel cost and price data are also presented in order to obtain a more complete picture of the nickel industry. Examination of labor cost and productivity data suggest that increases in labor cost have been offset by increases in productivity. Since labor cost represents a large proportion of the total cost of producing nickel in Canada, this result tends to suggest that total cost has been relatively constant over the time period considered. This conclusion should be viewed with caution, however, since the lack of adequate cost data for capital usage prevents a more rigourous test.

Empirical analysis of the real per-unit revenues of Canadian nickel producers for the time period 1895 through 1982 suggests a strong, increasing trend. This series represents the average unit revenue for all nickel sold by Canadian producers in various primary forms. The rising trend in per-unit revenues no doubt reflects the increased quality of Canadian nickel products over the years. As this series is not representative of the market price for constant quality refined/electrolytic nickel, real United States nickel prices over the time period 1840 through 1982 are also examined. This price

series follows a U-shaped pattern over time, first declining then increasing. The decline in prices in the late 1800's and early 1900's is quite dramatic and is due to the impact of the development of the Canadian deposits. The increase in nickel prices since the 1940's, due to a constantly growing demand, has not been large. Overall, real nickel prices are much lower now than in the early years of the industry. The analysis in no way suggests that real nickel prices will continue to rise; any price changes will depend on various market considerations. However, increasing nickel prices and per-unit revenues most certainly helped encourage the high level of entry into the industry over the years.

The present study has provided a theoretical model that more accurately describes the evolution of market structure and the change in resource prices over time for the nickel industry than previous studies. Those works have not been very descriptive of the nickel industry due to the use of restrictive and unrealistic assumptions in the analysis. That is, assuming that capital levels can be adjusted instantaneously, previous models have predicted that the industry will become more monopolistic over time. This result does not explain the history of the nickel industry. The present model, in which capital adjustment constraints are considered, leads to the conclusion that the industry will become more competitive over time. Further, the assumption that a resource is exhaustible results in the conclusion that resource prices will be increasing at an exponential rate over time. This study, by considering the impact of a substitute techology for the resource, concludes that the price of the

resource will be lower due to the substitute and will never rise above the price of the alternate resource.

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CHAPTER I

INTRODUCTION

1. Purpose of the Research

The purpose of this research is to analyze the pricing and production policies of the Canadian nickel industry. To this end, a general model of a nonrenewable natural resource industry is developed. It is assumed that the industry is dominated by a single firm. This firm is confronted with potential entry or expansion from a group of smaller, price taking firms that are referred to as the competitive fringe. The dominant firm sets the market price of the resource and allows the fringe sector to supply as much of the quantity demanded in the market as is profitable. The dominant firm then provides as much of the resource as necessary to maintain the price it has set. The model is used to determine theoretically the optimal pricing policy of the dominant firm over time and the effect of this policy on the entry and production decisions of the fringe firms. Further, the model is employed to determine the expected trend in market structure over time for the industry. The model provides a framework within which the pricing and production policies of the Canadian nickel industry from the 1930's to the present can be analyzed. During this time period the world nickel market evolved from an industry dominated by a single firm, the International Nickel Company (Inco), through a relatively lengthy period during which Inco acted as a price leader with varying degrees of competition from other firms, to the present situation, which approaches competition.

The main objective, then, is to analyze and explain this transition. One question to be answered centers on the optimality of a pricing policy followed by Inco which has encouraged entry into the industry with its resulting impact on market share. To answer this question the implications of the model concerning the trend in resource price and market structure are empirically tested using data from the nickel industry. A major conclusion of this study finds that Inco's pricing policy was indeed optimal from a long run point of view.

Several important studies provide the background for the topic addressed in the present analysis. The exploitation of an exhaustible natural resource controlled by a group of competitive firms or by a monopolist was first examined in the seminal work of Harold Hotelling (1931). The main conclusion from this study was that the rate of change of the resource price, net of costs, over time will be equal to the market interest rate. That is, as the resource is exhausted its value must be increasing to reflect its relative scarcity. This condition must hold in equilibrium, for if the rate of change of price were greater than the discount rate, the resource owner would not produce any output but would instead keep the resource in the ground and allow it to appreciate in value. If the rate of price increase was less than the rate of interest, the resource would be completely depleted in the given time period and the proceeds invested at the market rate of return. For a monopolist, the rate of change of marginal revenue, net of marginal cost, over time is equal to the interest rate in equilibrium.

The empirical investigation of various resource industries, however, fails to support such a conclusion. Harold J. Barnett and Chandler Morse (1963) have found that resources have not become more scarce but in several cases have become more abundant. Gerhard Anders, W. Philip Gramm, and S. Charles Maurice (1978) have determined that for fourteen mineral resources the price has grown at a rate significantly less than the market interest rate over the period 1900 through 1975. In addition, evidence from the copper industry, one of the most competitive mineral industries in the last century, indicates that real realized interest rates and real copper prices have often moved in opposite directions.

That these empirical results contradict Hotelling's conclusion is not surprising given the assumptions maintained in his analysis. These include certainty in reserve size, demand and production costs, the lack of substitutes or technological change, a finite resource stock, and the ability of firms to instantaneously adjust the level of capital utilized. Other studies have explored the effects of uncertainty, exploration, backstop technologies, and technological change on pricing and production decisions.[1] The present analysis focuses on the implications of the exhaustible resource model when constraints on adjusting capacity quickly exist for the fringe sector. Since the nickel industry has been characterized by steady growth, the results of the analysis are extended to the case of a

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[1]See Robert S. Pindyck (1980), Kenneth J. Arrow and Sheldon Chang (1982), Partha Dasgupta and Joseph E. Stiglitz (1981), and John R. Moroney (1982).

growing market demand.

Of particular importance to the research is the study of a non-renewable resource market characterized by a dominant firm competing with a group of smaller firms. Stephen W. Salant (1976) investigates the effect of a cartel, or dominant firm, on an exhaustible resource market. Two conclusions arise from this study; first, the cartel will eventually obtain a monopoly position in the industry, and second, while the fringe sector is producing, price is expected to grow at a rate equal to the market interest rate. Richard J. Gilbert (1978) obtains a similar result in which price may fall for a period of time as the fringe firms expand output.

The analysis used here assumes that the fringe sector takes price as given while the dominant firm sets price and serves the residual demand in the market. The primary tool used to derive the results is the calculus of variations, reflecting the fact that resource extraction involves intertemporal decision making. It is differentiated from previous dominant firm-mineral resource models in that production costs and the size of deposits are allowed to vary across sectors. Additionally, capacity constraints and limitations on the ability of any one firm to expand production quickly are incorporated into the model. Under conditions of binding constraints on the ability of fringe firms to adjust capacity the relationship between the rate of change of resource price and the interest rate is not expected to hold. The direction of change in market structure is also different from that predicted by previous models. The results of Salant (1976) and Gilbert (1978) hold as a special case of the

model when these constraints are nonbinding. The implications of the model are tested using traditional linear regression techniques.

The world nickel market provides for both an interesting case study and an empirical test of the model. It may well have been the best natural resource example of the dominant firm-price leadership model as characterized by economists. In the late 1920's nickel markets were dominated by one firm, Inco, which held approximately 90 per cent of the world market. Through the strength of its Canadian reserves and efficient production methods, Inco was able to maintain a market share that remained above 50 per cent, though declining steadily, through the mid 1960's. During this time period Inco was the industry's recognized price leader. Inco now holds less than 16 per cent of the market with little or no influence on price, and, for all practical purposes, the nickel industry can be viewed as competitive. Hence, it is a natural resource industry that, if viewed at different points in time, could be described as monopolistic, controlled by a dominant firm, and, more recently, as competitive.

An important area of investigation is to determine the forces that initially created monopoly but later resulted in entry and a more competitive market structure. This is of interest because Salant's and Gilbert's analysis of price leadership in a resource market predicts exactly the opposite time series trend in market structure. Thus, under the conditions that characterize the nickel industry, neither Salant's nor Gilbert's predictions hold. If these conditions more accurately describe oil markets than the assumptions embedded in previous analysis, then study of the nickel industry may

offer significant insight into the future structure of world oil markets.

The nickel industry is characterized by a wide variation in costs and deposit sizes across firms. Inco appears to have had a distinct cost advantage over the other firms in the industry for quite some time, as well as owning possibly the richest nickel deposit in the world. The time period required to bring a new nickel producing facility on line or to expand existing capacity is relatively long compared to other resource industries. This is due to the fact that most nickel deposits are quite isolated. An infrastructure consisting of roads, energy sources, and employee housing, as well as the mining facility itself, must be constructed before production can begin, imposing an additional constraint on the firm. The present study, by incorporating these factors into the analysis, contributes a generalization of previous theoretical models. The constraint on adjusting capital quickly is introduced in an explicit, functional form. The implications of such a constraint when production costs vary across firms are developed. Finally, the conditions under which market structure is expected to evolve over time into competition, as opposed to monopoly, are obtained.

2. Organization of the Research

The present study generalizes the results of previous research, the purpose being to explain the changes in market structure as found in the nickel industry as well as in other mineral resource markets. It also explains why the rate of change in the resource price may not

be equal to the interest rate in equilibrium for a nonrenewable resource market. A review of the literature relevant for the present study can be found in Chapter II. This chapter will explain the basic natural resource literature which serves as the foundation for the present analysis. Section 2 of the review begins with a discussion of the classic paper by Harold Hotelling (1931) in which the framework for exhaustible resource economics originated. It is followed with the results of several studies which extend the basic model of Hotelling. These studies develop the importance of production costs, including the user cost of the resource, in the decision making process of the firms, as well as extending the analysis to the case of a renewable resource. In Section 3 some of the more recent extensions of the basic model are reviewed. These studies are concerned with the existence of intertemporal biases in the production process and why such biases affect extraction paths, the implications of a backstop technology, or a substitute resource, which could become viable at a higher resource price, and the assumptions yielding market structures different from that of either competition or monopoly.

Section 4 next reviews the most important papers concerned with the effects of uncertainty in resource extraction. These papers examine uncertainty in the size of the resource and the demand for the resource. Section 5 reviews the literature in industrial organization that is particularly relevant for the study of the nickel industry. While some of the papers deal with resource markets, most are more general. Given the structure of the nickel industry, the

area of concentration of the studies reviewed is in the theoretical behavior of markets characterized by a dominant firm, a price leader, or by limit entry pricing. The final part of the review, Section 6, examines the results of several empirical investigations of various resource industries.

As the present study is concerned with explaining the events which have occurred in the nickel industry, a comprehensive review of the industry is presented in Chapter III. A discussion of the early history of the nickel industry can be found in Section 2, which chronicles the development of nickel into a true resource. Section 3 relates some of the obstacles which had to be overcome in the formative years of the nickel industry. The emergence of Inco as a dominant firm in the industry is outlined in Section 4. In Section 5, the role of Inco as a price leader and as the developer of new products and markets for nickel is stressed. The amount of entry encouraged by Inco's success and the problems these firms ran up against in developing nickel reserves are also documented. In Section 6 the loss of Inco's dominant position in the industry is discussed. This decline is attributed to the combined effects of a constantly expanding supply of nickel from other producers and a decrease in the growth rate of nickel demand. To help provide a more complete picture of the industry, data from the nickel industry concerning prices, production, and market shares over time are also presented.

The theoretical model developed for the research is described in Chapter IV. The model is quite technical at times but the major results are summarized in a manner that is easily accessible. The

basic analytical framework employed in the present study is explained in Section 2. The model assumes certainty in demand, deposit size and location, and in the costs of production. While these assumptions can be restrictive, they allow for an opportunity to analyze the evolution of market structure in a mineral resource industry characterized by the existence of a dominant firm. The conclusions resulting from the assumption of instantaneous adjustments in the level of capital are found in Section 3. In this instance it is shown that market structure can evolve from competition towards monopoly. In Section 4 the opposite result is shown to be possible under the condition of binding constraints on increasing the level of capital stocks for the fringe sector. An intermediate case, in which the fringe sector overcomes the capacity adjustment constraint quickly, is presented in Section 5. In Section 6 the results are extended to take into account a constantly growing market demand for the resource. Finally, the implications of a dominant firm in control of a limitless resource stock are discussed in Section 7.

An empirical investigation of the nickel industry is presented in Chapter V. Section 2 is concerned with the relative scarcity of nickel over time. Nickel prices and industry cost data are analyzed to test the hypothesis of increasing relative scarcity for nickel. Since the results obtained from the model that explain the trend in market structure in the nickel industry depend on the existence of constraints on increasing capacity quickly, the forms in which they may have occurred are summarized in Section 3. In Section 4 the implications of the model for the nickel industry are outlined.

Finally, the evidence concerning the trend in market structure and the change in resource prices to support the conclusions of the model will be presented in Section 5.

CHAPTER II

A REVIEW OF THE LITERATURE

1. Introduction

There exists an extensive literature which is concerned with the special set of circumstances found in nonrenewable resource industries. The nature of the problem centers on the efficient allocation of a finite resource stock across an endogeneously determined time horizon. The solution to this problem, as with any other, depends critically on the assumptions maintained in the analysis. Unfortunately, the analytical techniques which offer solutions often require the use of simplified assumptions which bear little resemblance to reality. This shortcoming can be overlooked when the simplified theoretical models describe in a reasonable fashion or help to predict accurately occurrences in the real world. However, general models do not apply well to particular situations, so that the need to improve upon an existing theory arises often. This fact becomes more apparent when the results stemming from the existing economic literature concerning mineral resource industries are compared to the special case of the nickel industry.

The purpose of this chapter, then, is to present a summary of those works which describe the traditional mineral resource model and to establish the framework upon which this present research is based. In Section 2 the fundamental models of resource extraction and their conclusions are presented. In Section 3 recent extensions of the basic model concerned with the effects of intertemporal biases and

backstop technologies in a natural resource industry are discussed. Section 4 considers the implication of uncertainty in the model, and in Section 5 the influence of different market structures on industry equilibrium are addressed. Section 6 presents the results of several empirical investigations of various natural resource industries. The reader without an interest in the more technical aspects of the problem may turn to the summary in Section 7, with no loss in continuity.

2. The Basic Hotelling Framework

The most frequently cited and indeed the most well known work in the area of exhaustible resources is that of Harold Hotelling (1931). Though the work was first published over fifty years ago, many of the questions posed by the author are still relevant today. Indeed, the framework developed by Hotelling is the usual starting point for most natural resource studies. Hotelling's purpose, as noted by others, was "...(1) to assess the policy debates arising out of the conservation movement and (2) to develop a theory of natural resources...".[1] The basic problem considered was to determine the conditions under which the exploitation of an exhaustible resource would be optimal, from both the firm's and society's point of view. Hotelling assumed that a firm holding a resource stock of known size would maximize the present value of its discounted profit stream. In a competitive market then, each firm would

$$\text{(2.1)} \qquad \text{Max } V = \int_{o}^{T} P(t)q(t)e^{-rt}dt$$

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[1] Shantayanan Devarajan and Anthony C. Fisher (1981) p. 66.

subject to $\int_0^T q(t)dt \leq S(0)$

by choosing q(t), where r denotes the rate of interest, P(t) denotes price net of production costs, S(0) denotes the initial resource stock of the firm, q(t) represents the firm's level of production in period t, and T the time horizon. Solving (2.1) yields the equilibrium condition

(2.2) $$P(t) = \lambda e^{rt} \text{ for all } t.$$ [2]

Noting that P(0) = λ, (2.2) can also be written as

(2.3) $$P(t) = P_o e^{rt} \text{ for all } t,$$

where P_o = P(0), the initial price as determined by supply and demand conditions in the beginning time period. This rule will hold since an owner of a resource stock will be indifferent between the price P_o for a unit of the mineral now and the price $P_o e^{rt}$ t time periods into the future. Differentiating (2.2) with respect to t and rearranging yields

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[2] The necessary condition (2.2) can be derived by forming the Lagrangian for (2.1);

(1) $$\ell(q,\lambda,P) = \int_0^T P(t)q(t)e^{-rt}dt + \lambda[S(0) - \int_0^T q(t)dt]$$

and then setting the partial derivatives of (1) equal to zero;

(2) $$\ell_q = P(t)e^{-rt} - \lambda = 0,$$

(3) $$\ell_\lambda = S(0) - \int_0^T q(t)dt = 0.$$

The solution to (1) then satisfies the equations (2) and (3). The Lagrange multiplier, λ, represents the marginal user cost of the resource. For a more detailed discussion of the Lagrange techniques, see Morton I. Kamien and Nancy L. Schwartz (1981) pp. 269-274.

$$\text{(2.4)} \qquad \frac{dP(t)/dt}{P(t)} = \frac{d\lambda e^{rt}/dt}{\lambda e^{rt}} = r$$

since $P(t) = \lambda e^{rt}$ for all t from profit maximization. Equation (2.4) is generally referred to as the Hotelling price rule. That is, in equilibrium the rate of change of net price over time is equal to the interest rate. This condition must hold in equilibrium, for if the rate of change were greater, the resource owner would not produce any output but would hold on to the deposit and let it appreciate in value. If the rate of change were slower, the resource would be completely depleted in the given time period and the proceeds invested at the market rate of return. Oliver Scott Goldsmith (1974) obtains a result similar to that of Hotelling by explicitly introducing the cost of production for each firm into (2.1). Instead of (2.2) the profit maximization condition for a competititve firm becomes

$$\text{(2.5)} \qquad p(t) - mc_i(t) = \lambda_i e^{rt}$$

where $p(t)$ is the market price, and $mc_i(t)$ is the ith firm's marginal cost of production. In equilibrium each firm equates market price to marginal production cost plus marginal user cost.

Hotelling also showed that social welfare maximization yields the same results as in the above case of a competitive market. But, he stressed that this finding did not justify a policy of non-government involvement in natural resource markets. This caveat is due to several considerations, the first of which has come to be known as the "common property problem". The basic problem is that whenever a good is owned by a group of individuals, the incentive for any one

individual to properly care for the good is less than if the good were owned solely by the individual. In the area of exhaustible resources, the classic case is that of a pool of oil. As a result of the inherent characteristics of the pool, the rate at which it is pumped from the ground greatly affects the total amount recovered from a given pool. If more than one individual owns rights to the pool, an inefficiently high number of wells may be drilled and the oil pumped at too fast a rate. The incentive is clear; if one lease owner pumps at the physically efficient rate, a different owner may be pumping at a faster rate in order to obtain a larger relative share of the oil. Unless there is some way to guarantee that all lease owners pump at the efficient rate, most likely none will.[3] In addition, if after costly exploration a firm locates a valuable resource on a tract of land, neighboring land owners are likely to earn large, windfall profits from the "... wild rushes ... to get hold of valuable property".[4] This return may or may not be justified from a social welfare point of view. Finally, it may not be proper to discount the value future generations place on the resource at the market rate of interest since their true preferences are unknown. This question is addressed at length by Robert M. Solow (1974) and

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[3]For an interesting discussion of the forms of contracting that have arisen in the oil industry to help insure that all lease owners of a given pool pump at the efficient rate, see Gary D. Libecap and Steven N. Wiggins (1984). This type of problem does not presently apply to the Canadian metal mining industry, though it could conceivably arise in the application of the apex law or in the context of pollution rights.

[4]Harold Hotelling (1931) p. 144, this possiblity arises only when it is believed that similar valuable deposits are located on adjacent land and the land is held privately.

will not be a matter of concern in the present study.

Hotelling next investigated the effect of the existence of a monopoly in the resource market. The monopolist's problem is basically the same as (2.1) except that now the firm is no longer a price taker. The monopolist realizes that any production decision it makes will have an immediate impact on the market price for the resource, that is,

$$P(t) = P(q(t)). \tag{2.6}$$

Substituting (2.6) into (2.1) yields the monopolist's maximization problem which is to

$$\text{Max } V = \int_o^T P(q(t))q(t)e^{-rt}dt \tag{2.7}$$

subject to $\int_o^T q(t)dt \leq S(0)$

by choosing $q(t)$, the monopoly output level. $S(0)$ is the initial resource stock of the monopolist. Solving (2.7) yields the equilibrium condition

$$P(q(t),t) + q(t)dP(q(t),t)/dq(t) = \lambda e^{rt} \text{ for all } t \tag{2.8}$$

Noting that the left hand side of (2.8) is simply marginal revenue (MR), net of marginal cost, it follows that

$$MR(t) = \lambda e^{rt} \text{ for all } t. \tag{2.9}$$

(2.9) can be employed to obtain a Hotelling rule for the monopolist

$$\frac{dMR(t)/dt}{MR(t)} = r. \tag{2.10}$$

For the monopolist the rate of change of marginal revenue, net of marginal cost, over time is equal to the interest rate in equilibrium. Assuming that the price set in the first period by the monopolist would be higher than that in a competitive industry, and taking for granted the tendency for a monopolist to restrict output, Hotelling argues that the effect of monopoly will be to reduce the rate of production and lengthen the time horizon compared to the competitive case.

Hotelling next looked at the effect of government taxes on the actions of a resource owner. In general, a tax that is not anticipated will have no effect on firm production plans and will merely redistribute income from the resource owner to the government. A fully anticipated tax on the value of the resource is shown to have the same effect as increasing the market rate of interest by the same amount as the tax, which tends to increase the rate of production. The implementation of a per unit of production tax (royalty) will tend to decrease the rate of extraction and increase the grade of the ore extracted but may also decrease social welfare.[5] Finally, Hotelling investigates a market where there exists more than one firm, but fewer than the amount necessary for a competitive market. It is expected that equilibrium would be characterized by prices that would be higher and production rates that would be lower than in the case of competition.

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[5]Other factors, such as capital allowances and exploration allowances, as well as various depreciation schemes can modify these results.

From the solution to (2.1), one of the conditions derived for profit maximization, (2.5), required that

$$p(t) - mc_i(t) = \lambda_i e^{rt}.$$

λ_i can be interpreted as the marginal user cost of production for firm i. Anthony T. Scott (1967) defines user cost as "... the present value of the future profits foregone by a decision to produce a unit of output today".[6] From this definition it must be the case that profits in the initial time period be greater than the discounted profits obtained through the future production that is lost by producing now, if there is to be any production. That is

$$R_i(t) - C_i(t) > U_i e^{rt} \tag{2.11}$$

if the ith firm is to operate in time period t, where $R_i(t)$ denotes the revenue function, $C_i(t)$ the cost function, and $U_i(t)$ is the user cost function, the value "... of which indicates for each rate of output today the total present value sacrificed by allocating that total amount of output to the present instead of the future".[7] Condition (2.11) is necessary but not sufficient for profit maximization; it is also required that:

$$mr_i(t) = mc_i(t) + MU_i e^{rt} \tag{2.12}$$

where mr is marginal revenue, mc marginal cost, and MU the marginal user cost. Noting that if the industry is controlled by a monopoly,

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[6] Anthony T. Scott (1967) p. 34.
[7] Anthony T. Scott (1967) p. 35.

$mr_i(t) - mc_i(t) = MR(t)$, and defining $\lambda_i(t) = MU_i(t)$, condition (2.12) is the same as (2.9). For a competitive industry, $mr_i(t) = p(t)$, so that (2.12) is equivalent to (2.5).

Scott went on to argue that another cost to be considered in profit maximization is the effect of cumulative production on costs. Given a finite, homogeneous ore body and a fixed technology for extraction; i.e., the absence of technical innovation in production, at some point production today will raise the cost of future production. Under these conditions this would be due to the simple fact that as the reserve is exploited the remaining minerals are found deeper and deeper in the mine and will have a higher cost of being brought to the surface. This cost is to be distinguished from that of switching to lower grades of the resource; the two phenomena affect costs independently but in a similar fashion. The effect of cumulative production on costs will be to lengthen the production time horizon compared to the situation in which cost remains constant as the resource is depleted. In a competitive market it is expected that the higher grades of ore will be extracted first, followed by lower and lower grades of ore. An additional cost or benefit to be considered, since it will affect the user cost directly, is the possibility of growth or decay of the resource. A high rate of decay lowers the user cost, while a high growth rate will raise it.

While the Hotelling rule has been derived from a model of profit maximization, Robert M. Solow (1974) obtains the same result by observing that a resource deposit is viewed as a capital asset by its owner in the same way as is a machine or building. Since "...

asset markets can be in equilibrium only when all assets in a given risk class earn the same rate of return," ... (which in this case is the interest rate for that risk class), then it must be the case that "... in equilibrium the value of a resource deposit must be growing at a rate equal to the rate of interest."[8] The value of the resource will be its net price, i.e., marginal revenue less marginal extraction costs. This does not imply, nor does the Hotelling rule, that the market price of the resource is increasing at a rate equal to the interest rate; market price could in fact be constant or falling if production costs are decreasing over time. The existence of a finite resource stock and the lack of any substitutes for the resource, however, imply that eventually market price must rise.

3. Recent Extensions

Hotelling's model as modified by the authors mentioned above lays the framework for most studies in an exhaustible resource setting. Recent work has centered around extensions of this model to allow for an investigation of the effects of intertemporal biases, backstop technologies, and market structure. The main purpose of including these factors is to determine how, if at all, the level of production and the path of prices over time is altered by their introduction.

James L. Sweeney (1977) suggests that several factors may be important in affecting the production plans of producers: the effect

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[8] Robert M. Solow (1974) p. 2.

of percentage depletion allowances with respect to a firm's ore body, market externalities, monopolistic structure in the industry, and price regulation. First, the conditions for equilibrium in a competitive market are determined and shown to be sufficient for social welfare maximization (in the absence of any externalities). Next, a market imperfection function, g(Q',t), is developed to measure the effect of each bias on the competitive outcome (Q' is output under the influence of the bias). g(Q',t) is, respectively for each of the above cases, the effect of the depletion allowance on marginal revenues, g(Q',t) > 0; the difference between marginal revenue and price, g(Q',t) < 0; the marginal social cost of the externality, g(Q',t) > 0; and the difference between the regulated price and the market clearing price, g(Q',t) < 0.

Using g(Q',t) and its rate of change compared to the interest rate, Sweeney arrives at the following conclusions from his maximization process: i) depletion allowances lead to higher present production and hence lower future production than would be the case in a competitive scheme where depletion allowances are not allowed; ii) the effect of a monopolistic industry is to slow down the production rate; iii) the production rate, given the existence of some market externality, will be higher, equal to, or lower than the competitive rate of production when all costs are internalized accordingly as the marginal social cost function grows at a rate less than, equal to, or greater than the rate of interest; and iv) the rate of depletion will be higher than, equal to, or less than that rate which the competitive solution dictates as the difference between the market clearing

price and the regulated price grows at a rate higher than, equal to, or less than the market interest rate.

Other authors, Solow (1974) and Joseph E. Stiglitz and Partha Dasgupta (1982), consider how the existence of a "backstop technology" can alter the rates of production of firms over time. Solow defines this alternative resource as "... a technology capable of producing a substitute for a mineral resource at relatively high cost, but on an effectively inexhaustible resource base".[9] Stiglitz and Dasgupta trace out the production path of a resource when there exists a backstop technology under varying market structures. It is shown that when both the resource and the substitute markets are characterized by competition, the rate of change of the resource price follows the interest rate (extraction costs are assumed to be zero for the resource) until it reaches the value $\bar{p}$, the minimum unit cost of production of the backstop technology. At this point the resource is depleted and the substitute is produced. A similar result is shown to hold when both markets are controlled by a single monopoly, the difference being that there is a slower rate of depletion of the resource in all time periods and a later introduction date for the alternative technology. Additionally, marginal revenue increases at the rate of interest as long as there remains any positive amount of the resource. When one of the markets is competitive and the other a monopoly, the period of extraction for the resource will be longer than if both markets were competitive but shorter than

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[9]Robert M. Solow (1974) p. 4.

if the markets were controlled by a single monopolist. The backstop technology is introduced at the same moment that the resource is exhausted.

For Stiglitz and Dasgupta, the interesting case arises when the resource and the resource substitute are controlled by two different firms. In a Cournot-Nash equilibrium, where both of the duopolists take the other's output level as given, the resource is exhausted at a later date than in the previous cases and the substitute is introduced before the deposit is completely depleted. There exists some time period during which the resource and the resource substitute are both produced. This is comparable to static models of limited competition where technologies of widely differing efficiency can be supported by the market during any given time period.[10] In a Stackelberg equilibrium, where the resource owner is the "leader" and the producer of the substitute the "follower", a similar result is obtained.

4. The Effect of Uncertainty

All the above models have been solved in a setting of complete certainty. By relaxing this assumption, a change in some of the results would be expected. An exhaustible natural resource industry

[10]The simultaneous production of both the resource and the resource substitute appears to be the more relevant case, as shown, for example, in the substitution of aluminum for copper in some but not all of its applications. In addition, while the initial price of aluminum was quite high relative to that of copper, technical innovation in production and entry from other producers led to price reductions and further substitution. The introduction of substitute, often superior, technologies is a continuing phenomenon, as evidenced by the recent use of fiber optics in place of copper in the communications field.

typically has many uncertain factors associated with it. For example, it is unlikely that a resource owner would know the true value of its marginal user cost, λ_i. User cost must be determined from present and future demand and supply conditions in the industry, as well as the true size of the resource stock. If these parameters are unknown, as is generally the case in actual mineral markets, then each resource owner will have its own "best guess" as to the value of λ_i. For instance, a resource owner, who believes that his reserve is smaller than it actually is, will act as if his marginal user cost is higher than it is in reality and subsequently overconserve on his deposit.

Kenneth J. Arrow and Sheldon Chang (1982) present an interesting approach to the problem of uncertainty in resource stocks. A model is constructed where resources are distributed randomly over a given land area and their actual sites are discovered through exploration. It is shown that the resource price increases following the Hotelling rule as known reserves are depleted. When price reaches some critical value, exploration is triggered which continues until new deposits are found. When the new reserves are found, price falls to a much lower level from which it increases over time, again following the Hotelling rule. This continues until the price of the resource again reaches the critical stage, at which point exploration begins anew and the process repeats itself. In this case, the price of the resource has no real long-run trend, though it does vary with the interest rate over shorter time horizons.

Milton C. Weinstein and Richard J. Zeckhouser (1975) consider the case of uncertain future demand for the resource. It is found that when producers are risk averse they tend to oversupply the resource in the earlier time periods, leaving a smaller resource stock for the uncertain future demand. When producers are risk neutral, the expected price changes according to the Hotelling rule and the extraction path is optimal.

Robert S. Pindyck (1978) extends the analysis by considering the effects of uncertain future demand and reserve uncertainty with exploration. Demand is modeled by assuming that it shifts randomly and continuously over time in such a way that as the time horizon increases, the level of demand uncertainty also increases. Reserves are modeled to fluctuate randomly over time via a similar stochastic process and are adjusted over time as new information becomes available from surveys and exploration or as a result of depleting the reserve. The firm's objective then is to maximize its expected discounted profit stream. Pindyck concludes that demand uncertainty does not affect the expected rate of change of price compared to the certainty case. Demand uncertainty is shown to increase the level of production in the initial period and to increase the rate at which production levels fall over time for the case of linear demand. For nonlinear demand the effect is indeterminate. The effect of reserve uncertainty will be to reduce the rate of price increases and raise the initial price when extraction costs are a nonlinear function of reserves. If extraction costs are constant or linear in reserves, then reserve uncertainty will not affect the rate of change of price.

In the model, exploration can be used either to reduce reserve uncertainty or to accumulate additional reserves. In the former case the expected rate of change of price will be decreased only when cost is a convex function of reserves and extraction cost rises as reserves fall. In the later case the expected rate of change of price will not differ from the certainty case, but the complete price trajectory may be higher or lower if the marginal physical product of exploration is either a convex or concave function of a random parameter, respectively.

Partha Dasgupta and Joseph E. Stiglitz (1981) consider the effect of uncertainty concerning whether or not a backstop technology will be produced to replace a resource in the market. Given a resource stock, it is shown that the rate of change of the resource price is faster than the interest rate for the time period before the substitute is introduced. When the backstop technology is found to be feasible to produce at a price $\bar{p}$, the price of the resource drops discontinuously to a price below $\bar{p}$, from which it then rises following the Hotelling rule. The resource price falls to a level such that by increasing at the rate of interest the deposit is completely exhausted when its price reaches $\bar{p}$, at which time production of the alternative technology comes on line. In effect, there is no time period in which the society is without either the resource or its substitute. When the date of introduction of the backstop technology is known with certainty, the initial resource price will be set so that it rises at the rate of interest; there is no incentive to produce the substitute until the resource has been exhausted and its

price is equal to $\bar{p}$.

Ngo Van Long (1975) models a resource owner facing the possibility of having its deposit nationalized. When the date of nationalization is unknown, the resource will be depleted at a rate faster than is the case when the date is known with certainty. The initial production level is higher and the time horizon shorter than in the certainty case. This result holds only in the instance that investment is irreversible and/or expected compensation is less than the present value of the resource stock at the date of nationalization. Ben S. Bernanke (1983) notes that the effect of irreversible capital investments coupled with future uncertainty about market conditions may lead to firms decreasing or delaying capital investments until additional information is obtained. That is, an investment will be made only if the expected return from the investment is greater than the cost of waiting for future market conditions to be known.

5. The Implications of Market Structure

Because of the nature of the nickel industry, it is necessary to consider those studies concerned with the impact of a cartel (or a dominant firm) on market equilibrium. Central to this topic is the behavior of a cartel with regard to its pricing, investment, and capacity policies. The conditions under which a cartel can successfully engage in limit pricing is also a relevant problem to investigate. A review of this research will lead to a better understanding of how a dominant firm in an exhaustible natural resource industry can be expected to behave.

An interesting case to study is that of a resource market characterized by either a monopolist threatened with entry or a dominant firm and a competitive fringe. Richard J. Gilbert and Steven M. Goldman (1978) consider the case of a monopolist in an exhaustible resource industry facing potential competition from other firms. The competition is kept from entering the market as long as the monopolist (the lowest cost producer) keeps price below the unit cost of production of the entrants, or as long as the monopolist production levels are large enough so that the effect of entry is to lower price to such a level as to cause the entrant to incur negative profits. The first case, "price triggered" entry, is rational when the potential entrants are small (i.e., entering the industry would have a limited impact on the monopolist's market share) and there are no irreversible investments associated with entering or exiting the industry. The alternative case, "quantity triggered" entry, will be rational when the potential entrants are large (i.e., having a substantial impact on the monopolist's market share) and there are irreversible expenditures associated with entering the industry.

The monopolist knows with certainty that, when either price reaches some critical value p^{ξ} or its remaining resource stock reaches a critical value S_1, entry will occur. Each case is then analyzed within a similar framework and the results compared to the instance where entry is prevented from occurring by some law or regulation. It is shown that in both cases the monopolist, threatened by entry from competitive suppliers, will produce at a lower rate and charge a higher price during the period before entry occurs than will

a monopolist unconstrained by the threat of entry.

The idea of a trigger price is similar to that of the "limit price" model as summarized by Franco Modigliani (1958). The traditional limit price model is based on three explicit assumptions concerning firm behavior:[11] 1) all firms attempt to maximize long-run profits; 2) existing firms can easily determine and set the appropriate "limit price"; and 3) existing firms believe that potential competitors will expect them to maintain their output levels when entry occurs, even though price may fall low enough to force negative profits on all firms (Sylos' Postulate).

In a competitive market entry is typically assumed to occur whenever market price is above the industry's long-run minimum average cost of production. This is not a reasonable condition for entry if the entrant can at all affect market price. The relevant price to base an entry decision on in this case is the expected post-entry price. Entry will not take place if the additional output will force price below the entrant's minimum average cost of production. The entrant rarely, if at all, faces an infinitely elastic demand at the pre-entry price P'. Instead it faces a downward sloping demand curve which is that part of the market demand curve to the right of P', the residual or marginal demand curve. P' is defined to be an entry preventing price if the long-run average cost curve is everwhere above the marginal demand curve. The limit price is then the highest possible entry preventing price. D. K. Osborne (1973) uses this type of

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[11] D. K. Osborne (1973) p. 71.

model to determine the conditions under which limit pricing would be rational. It is argued that an existing firm (or firms) would engage in limit pricing only when the profits obtained from such an activity were greater than those earned when entry is allowed.

Darius W. Gaskins (1971) was the first to investigate the path of an optimal limit price over time. A dominant firm facing entry in a market attempts to maintain an optimal market share through adjusting the price of the good. The dominant firm seeks to maximize the present value of its profits defined by:

$$(2.13) \qquad V = \int_{0}^{\infty} [\, p(t) - c \,] q(p(t),t) e^{-rt} dt$$

by choosing price, p(t), in each time period. V is maximized subject to the following constraints:

$$(2.14) \qquad \begin{gathered} q(p(t),t) = f(p(t)) e^{\gamma t} - x(t) \\ dx(t)/dt = k_{o} e^{\gamma t} [\, p(t) - \bar{p} \,] \\ x(0) = x_{o},\ \bar{p} \geq c,\ \gamma < r \end{gathered}$$

where q(p(t),t) denotes the dominant firm's level of output, c its average total cost of production (assumed constant over time), $\bar{p}$ the limit price (also constant), x(t) the level of competitors' sales, f(p(t)) the initial market demand curve, and γ the market growth rate. k_o, a positive constant, reflects the level of response of the competitors to the price set by the dominant firm.

dx(t)/dt and dp(t)/dt are obtained as necessary conditions for the solution of (2.13). By setting dx(t)/dt = dp(t)/dt = 0 and solving for the rival firms' equilibrium market share, comparative

statics can then be used to determine the effects of changes in the parameters on the pricing policy and market share of the dominant firm over time. It is shown that either a decrease in the interest rate or an increase in the dominant firm's cost advantage over the competition will raise the dominant firm's long-run optimal market share. An increase in the interest rate, the market growth rate, or the cost advantage of the dominant firm will increase equilibrium price. An interesting result of Gaskins is that if there is no market growth, then the market share of a profit maximizing dominant firm with no substantial long-run cost advantage will eventually decline. On the other hand, a growing market can lead to a higher market share for the dominant firm and higher prices even when the dominant firm has no real cost advantage over its competition.

In Gaskins' model, the dominant firm adjusts its output as competitors enter or exit the market. A problem in most limit price models is concerned with the validity of Sylos' Postulate; i.e, under what conditions will potential entrants believe that existing firms in the industry will maintain their pre-entry output levels after entry has occurred? For the assumption to hold there must be some mechanism by which existing firms can appear committed to the limit quantity so that if entry does occur it is not optimal for the firms to reduce their output levels and accommodate the entrants.

A. Michael Spence (1977) finds such an instrument when existing firms invest in excess capacity as a means of discouraging entry into the industry. The purpose of the idle capacity is to allow firms the ability to expand production quickly, and hence lower the market

price for the good, whenever the industry is threatened with entry. This has the effect of reducing the prospective profits of the entrant. When the existing industry sets output at the level conducive to the limit price, potential profits are nonpositive and entry is prevented.

In this model the existing firm (or cartel in the case of several existing firms) attempts to maximize:

(2.15) $$\pi(q,k) = R(q) - C(q) - rk$$

subject to $$q \le k$$ $$k \ge \bar{k}$$

where $\pi(q,k)$ denotes profits, $R(q)$ the revenue function, $C(q)$ variable cost, k the level of capacity, and r the cost of capacity.[12] The first constraint refers to the fact that production levels can never be greater than capacity. The second constraint is that industry capacity must not be less than $\bar{k}$, the entry detering industry capacity level; i.e., if existing firms produce at output level $q = k$, let $\bar{k}$ be the minimum level of capacity for which the following holds:

(2.16) $$p(q + x) \le AC(x)$$

where x is the output of an entrant and $AC(x)$ its average cost. $p(\bar{k}+x)$ then, is the limit price. That is, if the monopolist produces at a level of output equal to the limit capacity level $\bar{k}$, the effect

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[12] It should be noted that the structure of this model implies that a higher rate of interest in the market will lower profits and tend to discourage the use of excess capacity.

of any additional output from an entrant will be to drive market price below the average cost of production of the entrant. The Kuhn-Tucker conditions which give the solution to (2.15) for a producing firm are

$$\begin{aligned} R'(q) - C'(q) &= \lambda \\ r &= \lambda + \mu \\ \lambda(k - q) = 0,\ &\mu(k - \bar{k}) = 0 \\ \lambda,\ \mu &\geq 0 \end{aligned} \tag{2.17}$$

where λ and μ are the multipliers.

If the first constraint is met but not the second; i.e., $\lambda > 0$, $\mu = 0$ so that $\lambda = r$, then the unconstrained profit maximizing solution necessitates a capacity level at which entry is blockaded. If the second constraint is met and not the first; i.e., $\lambda = 0$, $\mu > 0$ so that $\mu = r$, then industry capacity is set at the limit price capacity $\bar{k}$ but not all the capacity is utilized. Cost is not minimized given the level of output supplied by the industry. If both constraints are binding; i.e., λ, $\mu > 0$, then capacity is set equal to $\bar{k}$ (to prevent entry) and so is output (to maximize profits). Price is equal to the limit price and entry is deterred.

In this model, the second case proves to be the interesting one. While Spence shows that in this case price is less than the monopoly price, it is still greater than the limit price. By maintaining excess capacity, existing firms in the industry can both deter entry and earn positive profits. If entry is threatened, the firms already in the industry can easily expand production to the limit price out-

put at which any entrant would be earning negative profits. Given the existence of excess capacity, it is rational for the existing firms to do so.

Spence (1979) considers a similar problem for a market characterized by an undeveloped, growing industry. Firms must decide on optimal strategies for irreversible investments in capacity, product design, and research and development. The level of investment at a given time period is different across firms due to the timing of entry and constraints on growth. Certain firms may be in a position to reach such a level of investment so as to make additional investment by other firms unprofitable, thus assuring the preempting firm a dominant position in the industry. Each firm seeks to maximize:

$$V^i = \int_{\tau(i)}^{\infty} [\ \pi^i(k) - rk_i\ ]e^{-rt}dt \tag{2.18}$$

by choosing $k_i(t)$; where $k_i(t)$ denotes the level of capital, $\pi^i(k)$ the amount of operating profit, $k = k(k_1,\ldots,k_n)$, and $\tau(i)$ the time period in which the ith firm enters the industry. It is assumed that $\partial\pi^i(k)/\partial k_i > 0$ and $\partial\pi^i(k)/\partial k_j < 0$ for $i \neq j$. V^i is maximized subject to the following constraints:

$$B_i(t) = D_i + \int_{\tau(i)}^{t} [\ \pi^i(k) - m_i\ ]e^{-rt}dt \geq 0 \tag{2.19}$$

$$m_i \leq \phi(k_i) \tag{2.20}$$

where D_i denotes the initial investment in the business, $m_i(t)$ the level of investment in each time period ($m_i = dk_i/dt$ if there is no depreciation), and $\phi(k_i)$ is an increasing function of k_i. Equation (2.19) is simply a financial constraint which requires that the firm

remains liquid. Equation (2.20) is a constraint on the physical growth of the firm in each time period, optimal investment levels cannot be achieved instantaneously but must be built up over time. Solving (2.18), each firm invests until the present value of the net marginal profitability is zero, i.e.:

$$\text{(2.21)} \qquad \int_{\tau(i)}^{\infty} [\ \pi^i_i(k) - r\ ]e^{-rt}dt = 0$$

where $\partial\pi^i(k)/\partial k_i = \pi^i_i$ for all i, j.

Since $\pi^i_{ij} < 0$, $(\ \pi^i_i - r\ )$ is either decreasing or constant as other firms are investing or are not investing. Therefore, each firm has the incentive to invest as rapidly as possible until some target level of capital is achieved. The first firm in the market can, by investing quickly enough, make entry by other firms unprofitable. On the other hand, a high level of investment by entrants can sometimes force the existing firm in the industry to accommodate them.

Stephen W. Salant (1976) investigates the effect of a cartel (or dominant firm) on an exhaustible resource market. Each firm is assumed to begin with an equal amount of the resource and all have an identical cost function. A cartel is formed when two or more of the firms are brought under the control of one of the resource owners. The cartel, by virtue of having the largest reserve, is able to maintain considerable influence on the resource price. The smaller firms not in the cartel remain price takers in the industry and will be referred to as the competitive fringe. The optimal strategy of the cartel is to choose a sales path in which marginal revenue (net of the constant marginal cost) grows at the rate of interest over all

periods of positive sales. Price (again net of the constant marginal cost) must also rise at a rate equal to the interest rate for all time periods in which the competitive fringe has a positive stock of reserves. When the deposit of the fringe is completely depleted, price will rise at a slower, or equal, rate than the market rate of interest.

Market equilibrium is characterized by two phases. In the first phase both the cartel and the fringe are producing and price rises at the rate of interest. At some point when $P(t) = P^*$, the termination price, the fringe exhausts its reserves and exits the market. This begins the second phase, in which the cartel is the sole producer and price rises at a rate less than, and marginal revenue rises at a rate equal to the interest rate. The time horizon for complete depletion of the fringe's and the cartel's reserves will be longer than would be the case for a perfectly competitive industry but will be earlier than that expected if the industry was controlled by a monopoly. In addition, it is shown that the effect of forming the cartel is to increase the total discounted profit stream of the fringe by a larger percentage than the increase in that of the cartel. This result follows since the fringe receives the benefit of the cartel's restriction in output, a higher market price, without having to restrict its own output. The cartel is also forced to sell part of its deposit during the second phase of equilibrium during which time the discounted price is below the initial price.

Gilbert (1978) considers a similar model in which the price of the resource cannot rise above the limit price $\bar{P}$, a price just below

the cost of producing an alternative technology. The cartel maximizes profits by choosing a price path supported by its level of sales. The rate of change of price is equal to the interest rate until it reaches the limit price, above which it cannot increase. The fringe will have exhausted its deposit at least by the time price reaches the limit price and from then on the only firm producing will be the cartel. The cartel cannot exploit its monopoly power since its actions are constrained by the existence of the substitute technology. If there exist any capacity constraints on the level of fringe production, price may actually be falling for a period of time as the competitive sector expands its capacity. Once the constraint is removed through sufficient expansion, price rises at the rate of interest up to the limit price.

Tracy R. Lewis and Richard Schmalensee (1980) modify Salant's model by investigating the effect of the industry being oligopolistic. A firm maximizes its discounted profit stream by choosing its output path over time subject to its resource constraint. Each producer takes as given the production plans of all other firms. An equilibrium is said to exist when no single firm can increase its profits by changing its output schedule. It is shown that an equilibrium does exist and that when the number of firms in the industry is finite and greater than one, the rate of change of price will be lower than the interest rate, while the rate of change of marginal revenue will be greater than the interest rate (both net of the constant marginal cost). When the costs of all firms are equal, a firm with a higher level of reserves will produce more in each time period

than those firms with smaller reserves, but the rate of production will be decreased compared to the case of equal costs and equal reserves. For the instance where both costs and reserves are different across firms, it is found that firms with differing levels of costs will produce simultaneously during some time periods. Additionally, it may be that firms with higher costs will at some time be producing less and at other times be producing more than lower cost firms and could also exhaust their deposit at an earlier time period.

Mukesh Eswaren and Tracy R. Lewis (1982) further extend Salant's model by incorporating the acquisition of reserves by firms through competitive exploration. The cartel maximizes its discounted profit stream by choosing a price path supported by its sales subject to a resource constraint and the supply response of the fringe. It is found that shifting reserves from the fringe to the cartel raises total industry profits, both the cartel and fringe firms which still hold reserves are better off. If there exist n unowned reserves each of size Δ, it will always be profitable for the cartel to acquire some amount of the new deposits.[13] If Δ is large and n is small, it is profitable for the cartel to acquire most of these reserves. On the other hand, if Δ is small and n large, it is not profitable for the cartel to obtain any great amount of the reserves, the majority are acquired by the fringe firms. The cartel can, by setting a lower price path, depress the value of the new deposits to the fringe and

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[13]The reserves are unowned in the sense that neither the cartel nor the fringe firms maintain ownership. The reserves are typically held by the government and some costs must be incurred before ownership passes to the developer.

make it optimal for the cartel to obtain all of the unowned reserves.

6. Empirical Evidence

An important implication of the Hotelling type exhaustible resource model is that net price is expected to increase at an exponential rate over time. Several authors have provided criteria by which this result can be tested. Harold J. Barnett and Chandler Morse (1963) and later Barnett (1979) test two forms of the hypothesis of increasing resource scarcity. The strong form of the hypothesis states that the real per unit cost of extracting a resource will be increasing over time. This result is expected due to the physical limits on the quantity and quality of any resource. To test this hypothesis real costs of extraction are measured both in terms of labor per unit of output and labor plus capital per unit of output. Such measures are constructed for the United States mineral, forestry, fishing, and agriculture industries, as well as a combined measure of all extractive industries. The first study considers the time period from 1870 up to 1957, while the second study extends the analysis over the time period 1958 through 1973. Barnett and Morse (1963) fail to find any evidence to support the strong hypothesis of increasing resource scarcity, in fact, the study indicated a declining per unit real cost for extracting resources. Barnett's (1979) results concur with the original finding, though there is some evidence that the decline in per unit cost has tapered off.

The weak form of the hypothesis suggests that even though per unit costs are declining, the per unit costs of production in the

nonextractive sector are also declining, but at a faster rate. This possibility is tested in two ways, first by determining the relative trend in extractive to nonextractive per unit production costs and by observing the trend in the relative price of products in the extractive sector. Barnett and Morse find that the weak scarcity hypothesis fails on both counts for the extractive sector as a whole, for agriculture, and for minerals. It is, however, supported for the forestry industry. Barnett (1979) extends the analysis to the years 1958 through 1973 by examining the relative productivity of labor in the minerals industry to that of manufacturing industries in various types of economies. The conclusion reached is that in most cases the weak scarcity hypothesis is rejected. Increasing relative scarcity, however, is not rejected in the case of coal in centrally planned economies and in developing market economies.

Employing an alternative type of approach, Gerhard Anders, W. Philip Gramm, and S. Charles Maurice (1978) perform a more direct test of the Hotelling rule. By examining the historical trend in resource prices an approximation of the cost (or benefit) of withholding a unit of an exhaustible resource from the market can be determined. The price of the mineral resource at the end of a certain time period is compared with the return received from selling a unit of the resource at the beginning of the time period and then investing the amount received at the market rate of interest. If the price of the resource at the end of the time period is less than the return to the investment, then it would have been optimal to have sold the resource at the beginning of the period. If it were more,

then it would have been optimal to withhold the resource from the market and allow it to appreciate in value. Anders, Gramm, and Maurice (1978) compare the price of a resource after a seventy-five year period with the return from an investment equal to the value of the resource at the beginning of the period. Fourteen mineral resources are considered, as well as four possible rates of return for the investment.

For each of the resources tested, it would not have been optimal to have withheld any of the resource from the market for the time period considered. In the case of nickel, the price for a unit of the resource in the year 1900 was $0.27 U.S. If this amount had been invested at the Moody AAA interest rate for the next seventy-five years it would have been worth $7.76 U.S. Given that the price for nickel in 1975 was $2.10 U.S., it is clear that any stockpiling of nickel would not have been beneficial. This result also implies that the rate of change of the resource price was considerably less than the interest rate, evidence that the Hotelling rule has not held.

Anders, Gramm, and Maurice next identify any periods in time over which it would have been optimal to withhold the resource from the market. In the case of nickel, it would have been worthwhile to keep nickel off the market for one year in anticipation of a price increase for only twenty-nine out of the seventy-five years, if those years could have been correctly identified before hand. If the annual rates of shareholders' equity in manufacturing is employed in place of the Moody AAA rate, there would then be only seven years in which it would have been optimal to withhold nickel from the market.

Similar results are obtained for the other mineral resources considered.

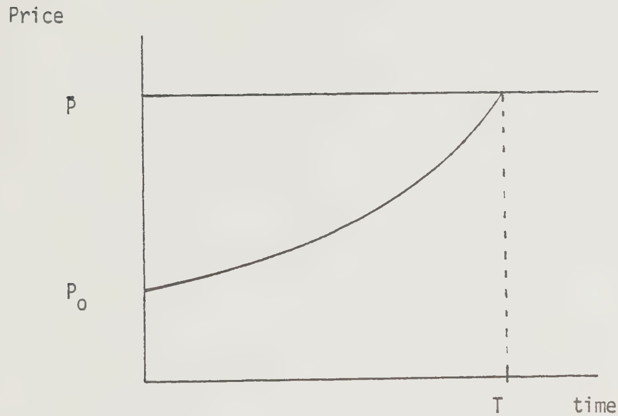
Margaret E. Slade (1982) analyzes the path of real resource prices over time. The prices are tested for the existence of both a linear and quadratic time trend. The main conclusion of the study was that a quadratic time trend appears to provide a better description of mineral resource prices over time. That is, in most cases the real prices of individual minerals more closely follow a trend that is first decreasing and then later increasing as opposed to a trend that is either increasing or decreasing only. For example, real nickel prices are examined for the time period 1900 through 1980. It is shown that the trend in nickel prices can be explained by both a linear and quadratic trend. Contrary to the general conclusion, however, it appears that an increasing linear trend provides a better description of nickel prices over time. This result is retested in Chapter V.

7. Summary

The work of Harold Hotelling (1931) has maintained a major influence on the exhaustible resource literature since it was first published over fifty years ago. Two major conclusions stem from this study which also characterize the results of more recent work. First, for the exhaustible resource market to be in equilibrium, price less marginal production costs (net price) must equal the marginal user cost of the resource if the industry structure is competitive, and marginal revenue less marginal production costs (net margi-

nal revenue) must be equated to the resources' marginal user cost if the industry is controlled by a single firm. This result simply extends the microeconomic analysis of a profit maximizing firm to the case where the total level of production is fixed and must be allocated over competing time periods. The marginal user cost, which represents the foregone future profits lost from the production of an additional unit of output in the present time period, is a true cost of production which is expected to increase as output rises.

The second result claims that net price in the case of competition and net marginal revenue in the case of monopoly must increase at an exponential rate equal to the market rate of interest over all time periods of positive production. The result is expected to hold because if net price (net marginal revenue) was growing at a rate slower than the interest rate, the firms (firm) would completely exhaust their reserves and invest the proceeds at the market interest rate. If net price (net marginal revenue) was increasing at a faster rate, then the firms (firm) would cease extracting the resource and allow it to appreciate in value. Adjustments in production, therefore, guarantee that equilibrium in the industry will be attained. This result is generally referred to as the Hotelling price rule and is shown graphically in Figure 1 for the case of a competitive industry. P_o represents the initial price of the resource which is growing at a rate equal to the market interest rate over time. As the price increases, the quantity demanded is falling over time as shown in Figure 1. Quantity demanded just falls to zero at the time the resource price reaches $\bar{P} = p_o e^{rT}$.



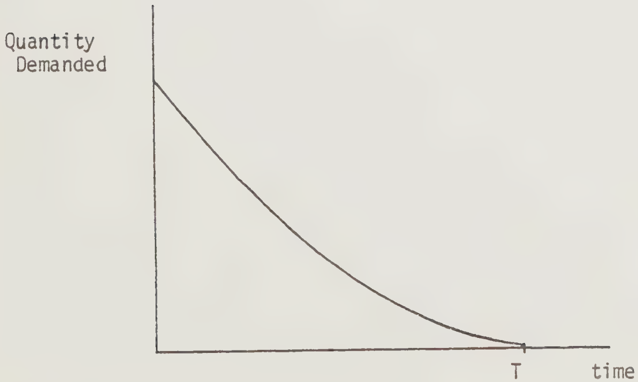


Figure 1.
The Path of Prices and Quantity Demanded Over Time: A Competitive Resource Industry.

Robert M. Solow (1974) arrives at a conclusion similar to that of Hotelling through quite a different approach. Solow argues that a resource owner will treat his deposit in the same manner as any owner of a capital asset. The rate of return for any asset must be the same for all assets of similar risk if the market is in equilibrium. The rate of return for the resource owner must then be equal to the interest rate which implies that the value of the reserve is increasing over time.

Together, these conclusions necessarily imply that the market price of the resource will be increasing over time as it becomes more scarce. The use of the word "scarce", however, should by no means imply the idea of shortages of the resource existing at any point in time. The idea of a growing resource shortage, as stressed by many of the "doomsday" writers, is based on the extrapolation of historical consumption and production trends into the future and not on any economic theory. The conclusions derived from the extrapolations tend to suggest that the rate of consumption of a resource will be increasing much more rapidly than the rate of production, which may even be decreasing, leading to severe shortages of the resource at some future date.[14] The Hotelling model, on the other hand, predicts that as the resource is exhausted its price will be growing at such a rate over time that the desired level of consumption of the resource will eventually decline. When the last unit of the resource is

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[14] S. Charles Maurice and Charles W. Smithson (1984) provide a summary of this line of reasoning. The authors also cite several convincing cases which show the inadequacies of such thinking.

extracted and sold, its price will be sufficiently high so that no more of it will be demanded.

The available empirical evidence, however, fails to support the implications of the Hotelling model. Harold J. Barnett and Chandler Morse (1963) tested to determine if resources have become relatively more scarce compared to other goods over time. Their findings imply that the level of scarcity is not increasing, and in some cases may even be decreasing. In a study of fourteen mineral resources Gerhard Anders, W. Philip Gramm, and S. Charles Maurice (1978) are not able to identify a single resource for which the rate of change of price was equal to the interest rate, but instead found that the rate of change was significantly lower than the interest rate in all cases. These findings suggest that the resources have been extracted at too slow a rate from an efficiency point of view.

The apparent inability of the Hotelling model to explain events in the real world can be attributed to the restrictive assumptions, both explicit and implicit, employed in the analysis. The first of these requires that the size and location of all reserves be known with certainty. Casual empiricism suggests that this is not the case as new deposits of minerals are discovered every day and the actual size of the reserve is questionable at best. Robert S. Pindyck (1978) incorporates uncertainty of the resource size into the Hotelling model and reports that the uncertainty leads to a higher initial price of the resource which then increases at a slower rate than in the certainty case. The conclusion stems from the idea that the firm will decrease its rate of production in the early time periods in

order to insure having some of the resource available for a later date. As time goes on and the true extent of the deposit is revealed, the firm can increase its rate of production with little fear of exhausting the reserve unintentionally. This problem of uncertainty in reserves is an important consideration given the history of Inco's proven ore reserves which have more than doubled over the time period 1933 through 1974. Inco's reserve ratio, the reserves in any particular year divided by that year's rate of production, has fluctuated in the range of a seventeen to twenty year supply with no real trend, up or down, since the early 1950's.[15]

One further question to be raised at this point is whether or not a mineral resource is truely exhaustible. While the quantity of a mineral extracted from any one location is finite, the amount of the mineral that could be found all over the world, or all over the solar system for that matter, may well be limitless. Kenneth J. Arrow and Sheldon Chang (1982) argue that as any group of reserves are exploited the price of the resource will be following the Hotelling price rule. However, when the price reaches a certain level exploration for a new deposit is triggered. The exploration continues until suitable new reserves are found, at which point all further exploration stops and the price of the resource drops discontinuously from where it again increases following the Hotelling rule. This process is continuously repeated so that there is no discernable long-run trend in the resource price. However, the expected short-

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[15] A more detailed account of the Canadian nickel ore reserves can be found in Gerhard Anders and T. P. Mohide (1980).

run trend in resource prices predicted by this analysis has not been shown empirically.

A distinction must be made between the terms exhaustible resource and exhaustible reserve. While it is easy to believe that any given mineral deposit will eventually be exhausted, the idea that at some date a given resource will be exhausted is almost impossible to imagine, and with good reason. Most mineral resources have a distribution which can be described with a resource pyramid, as shown in Figure 2. The highest level of the pyramid represents those reserves which are of the best quality but are also of limited quantity. The middle tier represents ore bodies of a lower quality but which are in a more abundant supply. The lowest level reflects an almost infinite source of an extremely low grade ore of the resource.[16] In this case "...society never physically runs out of any nonrenewable resource; however, all of the elements are so mixed in rocks and seawater that as we go to ever leaner ores, the costs per unit of product in dollars, energy, and environmental degradation continually increase, with occasional respites when new technology, better suited for the leaner ores, is developed and adopted."[17]

In order to move down the resource pyramid, then, either higher production costs must be incurred or technological innovation must occur. In either event, the high grade reserves will be exploited

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[16] It should be noted that this pyramid only covers primary metal production. To be realistic, it would have to be complemented by a representation of secondary supply; that is, the potential future supply coming from scrap metal.

[17] H. E. Goeller (1979) pp. 150-151.

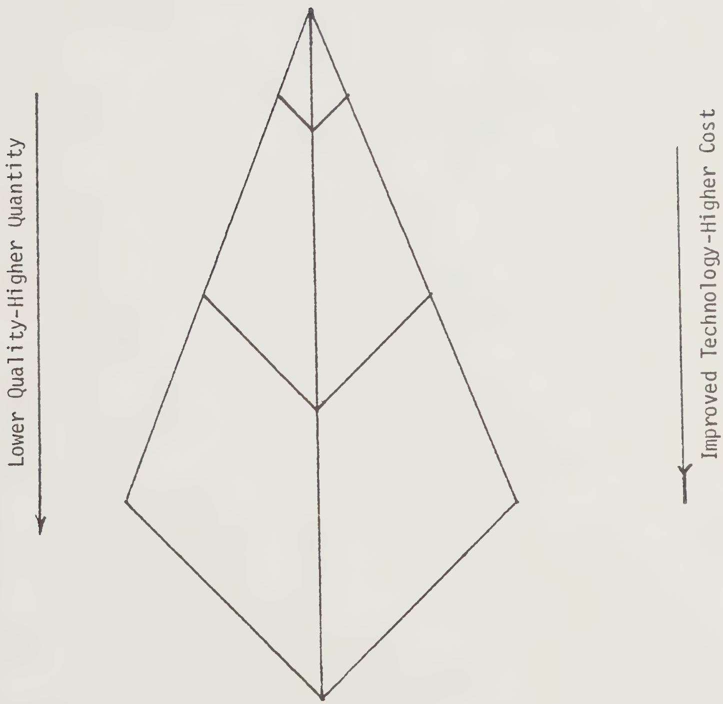

Figure 2.
The Resource Pyramid.

first and a movement to lower quality reserves will not occur unless there is some incentive, typically higher resource prices, to do so. The resource pyramid can be employed to show the virtual nonexhaustiblity of nickel as a resource.[18] The top of the pyramid represents the high quality nickel ores containing nickel similar to those of the Sudbury Basin area in Ontario, Canada. These ores also contain copper and small amounts of various precious metals. At one point, production from the Sudbury reserves provided for over 90 percent of the world's nickel.

As the price of nickel has risen over the years, an increasing percentage and absolute quantity of nickel is being obtained from reserves of lower quality than the Sudbury ore. These reserves are scattered around the world with the more prominent deposits being found in Australia, Cuba, New Caledonia, the Philippines, and the U.S.S.R. While the Sudbury area remains the world's single largest source of nickel, its importance is diminished when compared to the combined reserves of these lower quality sources, as shown by the middle part of the pyramid. In contrast, an extremely large supply of nickel may be obtained through dredging of manganese nodules from the ocean floor. These sea bed nodules are found in most of the earth's water bodies and provide a low grade nickel ore. The cost, however, of obtaining such nodules is prohibitively high and while research related to the technology of doing so is presently being undertaken, it is not likely that this source will be exploited on

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[18] For an application of this theory to Texas oil fields see Stephen A. Holditch and David E. Lancaster (1982).

any large scale in the near future.[19] One point which must be stressed is that in order for a society to move down the resource pyramid towards the possibly unlimited resource stock technical innovation must occur and the resource price must be rising over time to provide an incentive for firms to incur the higher costs of production.

A second critical assumption employed by Hotelling is that there does not exist any viable substitute for the resource. Many real world experiences, such as the substitution of petroleum for whale oil or synthetic rubber for natural rubber,[20] imply that this is not a realistic assumption.[21] Partha Dasgupta and Joseph E. Stiglitz (1981) introduce a backstop technology with a perfectly elastic supply at a given price into the analysis. When the date of innovation of the substitute is known with certainty, the price of the resource may initially be lower than in the case of no substitutes but will still increase at a rate equal to the discount rate. In the case of an uncertain innovation date, price will increase at a rate faster than that dictated by the Hotelling rule until innovation occurs. At this time price drops to such a level that by following the pricing rule from then on the resource is exhausted when its price is equal to the cost of the backstop technology.

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[19] For a more detailed account of the implications and the nature of sea bed mining see Gerhard Anders and T. P. Mohide (1980).

[20] See S. Charles Maurice and Charles W. Smithson (1984) for a discussion of these and other situations where new substitutes were developed in response to higher resource prices.

[21] The importance of substitution in the idea of nonexhaustibility of a nonrewable resource is addressed by H. E. Goeller (1979).

A third assuption made by Hotelling concerns the form of market structure found in the industry, either competitive or monopolistic. Tracy R. Lewis and Richard Schmalensee (1980) consider the implications of an oligopolistic industry. It is shown that the rate of production will be greater than in the case of monopoly but less than that of competition. Further, price is expected to grow at a rate less than the interest rate while marginal revenue will grow at a faster rate. Stephen W. Salant (1976) and Richard J. Gilbert (1978) have independently developed models of a resource industry characterized by a dominant firm competing with a group of smaller firms. It is shown that the fringe sector will exhaust its reserves at an earlier date than the dominant firm, allowing it to operate as a monopolist for the duration of the time horizon. While both sectors are producing, price is expected to follow the Hotelling rule, but once the fringe sector exhausts its reserves, price will be growing at a rate less than the interest rate. Darius W. Gaskins (1971) examines a similar market structure in the case of a typical manufacturing industry, which can be thought of as a case where a resource is available with certainty from various reserves of infinite size. It is shown that for a higher interest rate in the market the dominant firm, defined as the lowest cost producer, will sacrifice future market share in order to set a higher price for the product in the present time period, even when this is known to encourage entry into the industry. Further, a growing market demand can serve to maintain a higher share of the market for the dominant firm, even with high entry inducing prices being charged for the output.

One factor which complicates the analysis of a mineral resource is the possibility that a government might nationalize a resource industry once it has been developed through the efforts of private companies. Ngo Van Long (1975) investigates the implication of possible nationalization of resource deposits. When the date of nationalization is known with certainty by all firms and there exist no capacity constraints, the reserve will be exploited at such a rate that it will be exhausted by the time nationalization occurs. When there is uncertainty over the nationalization date firms will produce at a higher rate in all time periods and attempt to exhaust the reserve at an earlier date than in the certainty case. This conclusion is based on the reasonable assumption that the expected compensation for the reserve is less than the present value of the resource stock at the date of nationalization.

A final, implicit, assumption made by Hotelling is that firms are able to adjust the level of their capital stock instantaneously. Gilbert (1978) offers an intuitive solution to the problem of a dominant firm competing with a group of fringe firms when this assumption is relaxed. It is suggested that as the fringe firms expand capacity the price of the resource is expected to fall. This implies an inverse relationship between the rate of change of the resource price and the interest rate while the constraint is binding. Once the constraint on adjusting capacity has been overcome, price will follow the Hotelling rule as long as the fringe sector is still producing the resource. At some point the reserves of the fringe sector will be exhausted and the dominant firm will operate as a monopolist from

that point on. While this result is plausible, several specific cases suggest that it is not general. The early years of the aluminum, diamond, and nickel industries were all characterized by the existence of a dominant firm, or, for all practical purposes, a monopolist with virtual control of the market. In the aluminum industry it was Alcoa, in the diamond industry it was DeBeers, and in the nickel industry it was Inco. While prices were falling in the early years of the aluminum industry, diamond and nickel prices have been steadily increasing. Over the years significant entry has occurred in these industries, so that the market structure of each has become much more competitive. The most striking change has taken place in the nickel industry, where the share of the market supplied by Inco has gone from over 90 percent in 1929 to less than 15 percent in 1982. This finding is in direct conflict with Gilbert's intuition and with the more restictive model of Salant (1976).

This research will contribute to the existing literature a more rigorous analysis of the implications of constraints on adjusting capacity quickly for firms operating in an exhaustible resource industry. This analysis is more general in that Salant's results hold as a special case when the constraints are nonbinding. Gilbert's intuition also holds as one possible outcome in the instance where the constraints are binding. Further, and most importantly, the conditions under which market structure is expected to evolve from monopoly into competition, as in the nickel industry, are developed. The study will offer, then, a more general model of an exhaustible resource industry characterized by the existence of a

dominant firm competing with a group of smaller, price taking firms when there exists constraints on adjusting capacity quickly. Since the nickel industry has experienced a period of sustained growth in demand, partly in response to the research and development in new markets and products carried out by Inco and other Canadian producers, the implications of such growth are also considered.

An additional contribution of the study is an indepth investigation of the nickel industry. The first reason for doing this is to show that the assumption of instantaneous adjustments of the capital stock for a firm in an exhaustible resource industry may not be a very realistic one. In its place, it is argued that increasing the level of a firm's capital stock is a time consuming process. Secondly, the various forms in which the constraint actually appeared in the nickel industry are discussed. To this end the histories of the development of several nickel deposits located in various parts of the world are presented. Finally, the implications of the Hotelling, Salant, and Gilbert models are tested for the nickel industry. This will involve the application of previous tests of scarcity to the data obtained from the nickel industry.

CHAPTER III

THE NICKEL INDUSTRY: AN OVERVIEW

1. Introduction

The theoretical model to be presented in Chapter IV assumes the existence of a dominant firm or a cartel competing with a group of fringe firms. The dominant firm sets the market price for the resource and allows the smaller firms to provide as much of the resource as they wish at that price. The dominant firm then supplies any residual demand in the market. The model will be used to determine how market structure changes over time under different assumptions concerning the speed of capital adjustments. While the model is general in that it may be employed to describe any type of exhaustible resource industry, its primary purpose in this study is to describe the empirical history of the nickel industry.[1] As such, it is best to provide an overview of the industry at the outset.[2] A description of nickel markets cannot be complete without a discussion

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[1] The aluminum, copper, diamond, and oil industries, for example, would also provide for interesting applications of the model. The aluminum and diamond industries are similar to the nickel industry in that the early history of both were marked by the existence of a single dominant firm or cartel. In the oil industry a cartel did not appear until much later in the history of the industry, while in the copper industry several attempts at cartelization have failed. For a discussion of the impact of a cartel in the oil industry, see Stephen W. Salant (1976) and Richard J. Gilbert (1978). The model may also be applicable for the magnesium industry.

[2] Interviews with Gerhard Anders, L. G. Bonar, T. P. Mohide, Johannes P. Schade, and C. L. Warden (all in 1983) have provided valuable help in preparing this Chapter and are greatfully acknowledged. F. B. Howard-White (1963), D. M. LeBourdais (1953), and the Minerals Yearbook (Annual) were also important sources.

of the International Nickel Company (Inco), a dominant firm in the industry for over fifty years. Further, several case histories of the development of new nickel deposits must be presented in order to provide justification for a critical assumption made in the model concerning constraints on capacity adjustments.

The earliest utilization of nickel was purely coincidental and the occurrence of nickel in a body of ore was, at first, detrimental to its value. Section 2 describes the evolution of nickel from an undesired byproduct to a valued commodity. Section 3 outlines the events which characterized the beginning of the nickel industry and mentions some of the early difficulties which were overcome in its production. In Section 4 the reasons for Inco's dominant position in the industry are discussed, and in Section 5 some of the problems associated with the development of a nickel reserve are addressed. Section 6 describes the series of events that have led to the loss of Inco's dominant position in the industry.

2. Early History

The utility of nickel as an alloy with other metals has been traced to copper and bronze articles dated from 3500-3100 B. C. These artifacts took the form of coins, arrowheads, and knives, though the use of nickel in their manufacture was purely by chance. In the 17th century the metal from meteors was used to produce swords which were thought to bring good luck to their owners. The reason for this belief is now clear, the meteoric metal generally contained nickel which gave the sword an exceptional hardness. The importance

of the nickel could not have been known at the time since it was not identified as a separate element until 1751 by Axel Frederick Cronstedt. Fifteen years later nickel was found to be an important component of "white copper", a highly valued metal imported from the Orient, the manufacturing process of which had been held in secret. By 1825 a comparable alloy composed of copper, nickel, zinc, and iron was being produced by several individuals in Europe and within ten years in the United States.

Various alloys of nickel were soon employed in the production of candlesticks, bells, horse harnesses, plates, tableware, and coins. The first few firms involved in this production were able to maintain a reasonable level of profits, which certainly encouraged other companies to enter the business. One consideration which tended to impede entry though was the problem faced by producers of nickel based products in obtaining a steady supply of the metal. The early history of the nickel industry can be characterized by three major shortcomings; first, the lack of any developed deposits of suitable size, secondly, the need for a reliable refining process, and finally, the uncertainty of a future market for any large quantities of the finished nickel.

In the same manner that the first uses of nickel were purely by chance, luck, or the lack of it, played a major role in locating early nickel deposits as well. Silver deposits found in Schneeberg and Annaberg, Germany, and first worked in the mid 1400's, were plagued by the existence of a substance called *kupfer nicklichten* which made refining difficult and even hazardous to the health of the work-

ers. The health hazard was due to the presence of arsenic in the ore and until this was known it cast a dark shadow over nickel. It would take three hundred years before a use was to be developed for the nickel. Nickel was also found in various copper mines of the day, such as those in Mitterberg, Austria. In the late part of the 18th century through the middle part of the 19th century deposits located in Austria, Czechoslovakia, France, Germany, Norway, Poland, Sweden, and the United States were exploited mainly for the nickel ore they contained, though none of these deposits turned out to be very significant in size. As early as 1893 various nickel deposits were known to exist in Russia although the extent of these reserves was not realized until much later.

One important and early source of nickel was the island colony of New Caledonia. Claimed for France in 1853, an extensive study of the island's mineral resources was commissioned by the government in 1863. Within several years it became apparent that there existed large deposits of nickel on the island. Efforts to extract the ore began soon thereafter but more than twenty-five years passed by before an efficient large scale production system was in place. Several companies organized to exploit the reserves failed during this time period though development continued more or less steadily as other groups took their place. The development of the deposit was hampered by several complicating factors; first, there did not exist a reliable source of labor on the island, secondly, an insufficient number of ships were available to bring supplies to the island and transport the ore to Europe, and finally, furnaces had to be erected

in order to smelt the ore on the island.

3. Foundation of an Industry

At about the same time that Societe Le Nickel, a large scale producer of nickel in New Caledonia, had established itself as the leader in the industry, certain mineral deposits were being claimed near the area of Sudbury, Canada. First located in 1856 but then forgotten, the deposits were rediscovered in 1883 by a blacksmith laying track for the Canadian Pacific Railway. The deposits were exploited, at first, for the copper contained in the ore. However, refining the ore turned out to be a rather difficult process due to its high nickel content. A necessary prerequisite for the success of the Canadian mining industry would be the development of a means of separating the two metals found within the ore. Several refining methods already existed but they were very expensive to utilize and did not adapt well to large scale production nor to the type of ore found in Canada.

Deposits of nickel ore can be classified into three distinct groups; sulphides, laterites, and arsenical. The arsenical ores were characteristic of those mines first worked in Austria, Germany, and elsewhere. In conjunction with the nickel, arsenic, cobalt, and silver are typically found. The laterite ore, as was found mainly in New Caledonia, was mined for and contained only nickel. This type of ore was the simplest to refine. The sulphide ore, the type of the deposits at Sudbury, is rich in nickel, copper, and sulphur, as well as containing small quantities of gold, palladium, platinum, silver,

and other metals. This type of ore proved to be the most difficult to refine.[3] One solution to this problem was developed under the direction of Robert M. Thompson of the Orford Copper Company in 1891 and is usually referred to as the tops and bottoms method, a description of which follows.

> The Orford process is based upon the fact that if nickel and copper sulphides are fused with sodium sulphide the copper sulphides dissolve readily while the nickel sulphides dissolve only slightly. When such a fusion is cast and cooled it consists of a layer at the bottom of nickel sulphide containing only a little copper and a layer at the top of mixed sodium and copper sulphides containing very little nickel. The tops are separated and blown in a converter for blister copper. The bottoms are remelted for a second separation into tops and bottoms, the latter containing less than 1 percent copper. These second bottoms are crushed, leached to remove soda and iron, given a chloridizing roast, and finally leached to remove remaining copper. The nickel is recovered as oxide, which may be sold as such or reduced to nickel shot or pig, or to anodes for further refining by electrolysis.[4]

An alternate method was independently developed in 1892 by Ludwig Mond, a German chemist who had settled in England. He worked, along with an Austrian chemist named Carl Langer, in a research laboratory set up on Mond's property in London. A description of this process, which was quite different from the Orford process, follows.

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[3]For a detailed description of the different types of nickel ores that exist and the locations in which they are found see the report of the Royal Ontario Nickel Commission (1917).

[4]United States Department of the Interior (1934), p. 577.

> The Mond process is based upon volatilization of the nickel in the roasted bessemer matte as nickel carbonyl, $Ni(CO)_4$. The roast first is leached with sulphuric acid to remove copper. The nickel oxide is reduced to nickel by water gas at 350 C. The nickel is then converted to carbonyl by contact with CO gas at 50-100 C., and the carbonyl gas finally is decomposed into nickel and CO by heating it to 180 C. This is done in cylinders containing small nickel pellets upon which the nickel from decomposition of the carbonyl is deposited.[5]

Not originally being in the nickel business and not being able to sell his process to existing nickel producers, Mond soon decided to enter the nickel industry on his own by acquiring some Canadian mining claims. At the end of the 19th century about two-thirds of the world's nickel came from New Caledonia, the remainder was supplied chiefly by Canada. It would not be long before the size of the Canadian reserves allowed it to become the world's leading producer. By developing their respective refining processes both the Orford Copper Company and the Mond Nickel Company had guaranteed their futures.

With the beginning of the twentieth century came several events which were to shape the nickel industry for years to come. In 1902 the Canadian Copper Company, a mining concern located in the Sudbury area, and the Orford Copper Company, the New Jersey based refiner, were combined to form the International Nickel Company. Like the early groups organized in New Caledonia, this new venture had its share of problems to overcome. The smelters needed to be updated and were plagued by fires, the trains needed for transportation of the

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[5]United States Department of the Interior (1934), pp. 578-579.

ore were in sore need of repair, and the mines were experiencing a shortage of labor. The new company started forward with a bold plan for the consolidation and modernization of its facilities.

At about the same time in New Caledonia a second company began extracting ore. This was the Ballande Company, which at first did its refining in France and eventually in the United States. The war between Russia and Japan beginning in 1904 demonstrated the importance of nickel in armour plating, the use of which played a major role in the build up of navies prior to the first world war. In 1910 N. V. Hybinette developed a new process of refining nickel electrolytically. A small refining plant was started in Kristiansand, Norway which would grow into a substantial and successful operation.

The outbreak of the first world war placed extreme pressures on the young nickel industry. The International Nickel Company and the Mond Nickel Company responded with an unprecedented drive for the expansion of both mining and refining capacity. The International Nickel Company nearly doubled refining capacity at their Bayonne, New Jersey refinery and also began construction of a new refinery in Port Colbourne, Canada. The Mond company also began an expansionary program. Le Nickel, in New Caledonia, did not fair quite so well as the war seriously hampered the delivery of coal and coke to the island and shipments of nickel matte to Europe. While the allied forces had control of an expanding supply of nickel from Canada, Germany was hard pressed for nickel and went so far as to requisition household articles containing nickel, withdraw certain coins with a nickel base from circulation, and reopen several marginal nickel mines located in

the territories it held. The Canadian nickel industry as a whole met the challenge of the war head on; between 1914 and 1918 its output of nickel more than doubled. The years following the war, however, would prove to be even more challenging for the industry.

4. A Dominant Firm Emerges

At the end of the war there were two major sources of nickel ore, four different and economically viable means of refining the various types of ore, and an unprecedented level of available capacity, some more of which was not yet completed. The problem faced by the nickel industry was that previous to and during the war years 80 percent of all output was consumed by industries tied to the military. After aggressions ceased, the munitions market practically vanished. Essential to the future of the nickel industry was the development of new uses for nickel in other, peacetime markets. The International Nickel Company and the Mond Nickel Company both set out to achieve this goal, though the first few years following the war were marked by plant closings and idled capacity throughout the industry. This search for new markets turned out to be highly successful though, and within a decade yearly peacetime consumption of nickel had exceeded that during any of the war years.

Besides the growth in outlets for nickel production during the 1920's two other significant events occurred at the later end of that decade. First, and having the largest impact, was the absorbtion of the Mond Nickel Company by the International Nickel Company, which by now was referred to as Inco, in 1929. The impetus for the merger was

the realization that the two companies held in common an extremely large deposit of nickel, the Frood Mine and the Frood Extension. It was believed that a great savings could be made if the deposit was worked by one firm instead of two. In its first year of operation the new company supplied over 90 percent of all nickel consumed in the world.

Another important event in 1929 was the organization of Falconbridge Nickel Mines Limited, located in Falconbridge, Canada. Though other groups had previously attempted to enter the industry, none had been successful since the Ballande venture in 1904. Falconbridge succeeded where other firms had failed because it had the three ingredients necessary for a nickel producing company to survive; a suitable deposit from which the nickel ore could be obtained, a refinery with which the ore could be processed, and a ready market for the finished nickel. In Canada, Falconbridge held mining rights to several large deposits in the Sudbury basin, it had acquired the Kristiansand refinery in Norway, and it was content to concentrate on supplying the expanding European market.[6]

The stock market crash of 1929 in the United States certainly had an effect on the demand for nickel and nickel based products. A low point in production was reached in 1932, but nickel markets rebounded in 1933 and began a sustained period of growth. During this era the principal use of nickel was in making iron and steel alloys, for which about 42 percent of all nickel was consumed. These

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[6]An indepth account of the Inco, Mond merger and the organization of Falconbridge can be found in D. M. LeBourdais (1953).

alloys were used in a wide variety of applications which called for heat resistant, corrosion resistant, or high strength metals. Nickel copper alloys consumed an additional 31 percent of nickel in various final products. The remainder of the nickel was used for nickel silver alloys, nickel plating, and storage batteries. Many of the different nickel alloys were consumed in the transportation and defence related industries.[7] In 1934 Canada was by far the leading producer of nickel, with New Caledonia a distant second. Combined the two contries provided more than 93 percent of the world's nickel, Canada's share being over 81 percent. The remaining 6 percent of nickel came from Burma, Germany, Greece, Morrocco, Norway, the U.S.S.R., and the United States. World production of nickel reached a new peak in 1934 of 71,600 metric tons, beginning an upward trend that would continue for more than forty years. Coincident with this growth in demand would be a general increase in the number of countries producing nickel as more deposits were discovered and developed. Canada, however, was to dominate the nickel industry for many years to come.

From 1930 through 1950 Canada supplied, on average, about 80 percent of the world market for nickel. The U.S.S.R. entered the industry as a nickel producer during this time period and slowly expanded its production so that by 1950 it provided almost 20 percent of the world's nickel. New Caledonia, on the other hand, would experience various difficulties and produce a relatively small amount

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[7] For a better appreciation of the many types and uses of nickel alloys see United States Department of the Interior (1934), pp. 578-579.

of nickel. Canada's share of the market would not fall below 50 percent until 1968. Several reasons surface as to how Canada was able to maintain its dominant position for such a long period of time. First is the sheer size of nickel deposits located in the Sudbury Basin area. At various points in time Inco has initiated exploration of its mining claims in the belief that its existing deposits were about to be exhausted. This exploratory drilling not only extinguished any such fears by uncovering new portions of the known deposits, but also located several new, large deposits in the Sudbury Basin area. To appreciate the extent of these deposits it should be noted that in 1933 Inco had proven ore reserves of 205 million short tons, over forty years later, in 1974, Inco's proven reserves were 414 million short tons, more than doubled.

The Canadian ore is also rich in other metals besides nickel. For example, every two pounds of nickel produced from the ore generally yield one pound of copper, as well as trace amounts of some precious metals. Ore from New Caledonia, on the other hand, has virtually no copper content. Finally, the nickel deposits of Canada are located in a centralized area, as opposed to those found in other countries such as the U.S.S.R., where they are much more dispersed over a wide area. The Canadian nickel industry was able to concentrate its development in one localized area and take advantage of economies of scale in transportation, power sources, smelting and refining. Other countries may require separate such facilities at each mine location.

5. Growth of the Industry

As argued above, for a new venture in nickel to be successful it must have control of an ore body, a refinery to process that ore, and finally a market in which it can sell the finished nickel. A market was practically guaranteed for a new producer by the continued growth in demand that characterized the industry. A good deal of this growth was due to the extensive research and development carried out by Inco to find new uses for the nickel. Developing a refining process was not too much of a problem either. While in general a new process is needed to accommodate the characteristics of an ore specific to an area, the new process is basically an adaption of one of the four major refining processes which had all been developed by 1930.

The main problem faced by those firms entering the nickel industry was in securing a producing body of ore from which the nickel could be obtained. This involves two steps, the first is to locate a nickel deposit and the second is to build the infrastructure necessary for mining activities. An early example of this is found in the development of a nickel deposit found in 1930 near Petsamo, Finland. Inco, which by then had over thirty years experience in the industry, was given the right to develop the deposit by the Finnish government. The exploratory work was begun in 1935 and continued into 1936, during which the first roads were built to reach the isolated deposits. Plans were soon drawn up to construct an electric railway and a hydroelectric power plant to serve the facility. A small shipment of ore was also sent to an Inco refinery for testing. In 1937 an eco-

nomically viable ore body was located and plans for a smelter were outlined. An adit was built to reach the ore body in 1938 with plans to connect it with a vertical shaft by early 1939. Also, housing for the workers was completed and construction of the smelter was started. In late 1939, work on the facility was halted due to the Russian invasion of Finland, the first Russo-Finnish war had begun. The mine itself was considerably damaged before a Peace Treaty was formalized with Russia in March of 1940. Soon after this point work was started to restore the mine with the assistance of German materials and engineers. It was announced in 1941 that the Germans had expended a great effort in finishing the facility and it was producing ore by June of that year.[8] Production of nickel reached a high of 8,970 short tons in 1943, but dropped sharply the following year. The land was ceded to the U.S.S.R. in 1944 and little information is available from then on. Still, it had taken over eight years in an effort aided by Inco and later the Germans to bring the development up to a reasonable level of production.[9]

In the same way that the first world war placed great pressure on the nickel industry to expand, so did the second. The need for nickel in armaments pushed demand to an all time high, and several obstacles had to be overcome to meet it. Inco lost its deposit in Finland to the Russians and then to the Germans, who later cut off Falconbridge from its refinery at Kristiansand. Le Nickel also lost

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[8] The ore produced was probably being sent to German refineries.

[9] For a more detailed account of the development of the Petsamo deposit see United States Department of the Interior, (1930-1948).

its refinery, located in France, to the Germans, and the situation in Southeast Asia hindered its mining and smelting operations in New Caledonia. The level of importance attached to Inco's reserves could not have been higher. Inco responded by increasing its mining and refining capabilities. These expanded facilities also allowed Inco to refine the nickel matte coming from Falconbridge.

Even though the United States had a steady supplier of nickel in Canada, the government was concerned that only a few small nickel deposits were located in the country. In an attempt to rectify this situation the government offered incentives for the exploration of its Cuban territories in order to locate a viable deposit. In 1940 the Nicaro Nickel Company began development of the Cuban deposits. In the same year a patent for the process of treating Cuban ore was granted in the United States. A pilot plant came into operation in late 1941 and plans were made for a full scale facility. Construction of the facility, financed by the United States government, was started in 1942 but at an accelerated pace due to the pressures of the war. A small amount of nickel was produced in 1943, though construction was still in progress. While output increased in 1944 as capacity continued to be expanded, doubts were raised as to the profitability of the venture once the war was over. Full scale production of sorts was finally reached in 1945 as the 1944 output was more than doubled. Despite some technical problems output increased slightly in 1946. As was feared though, the facility was not as profitable as a peacetime concern due to the post war drop in demand and prices, and production was abruptly halted in March of 1947. It

should be noted that even with the high pressure brought on by the second world war, the building of the infrastructure necessary for exploiting the deposit still required a good five years.

While the supply of nickel was limited in the early years of the war, the expansionary efforts of Inco yielded an adequate supply of nickel by 1944, though producer inventories were low for the remainder of the war. With the surrender of Japan to the allied powers in 1945 came the cancellation of war contracts and an abrupt drop in the demand for nickel. Once again Inco found itself with an unprecedented level of capacity but no certain outlet for its production. As before, the company began an energetic search for new products and uses of nickel to satisfy the deficiency. To a large extent this work was successful in that in both 1947 and 1948 peacetime records for consumption were set. However, this level was still lower than during the war years and a more than adequate supply was available up to 1950. This led to the withdrawl of nine producing countries from the industry in the years following the war.

In 1950 only five countries were producing nickel, the largest producer by far being Inco of Canada. In fact, Canada provided for over 76 percent of the market that year. The world surplus of nickel soon turned into a shortage as the war in Korea began to heat up. This event, along with the expectation of continued growth in demand from the private sector, encouraged a period of sustained exploration and expansion in the industry. Sherritt Gordon Mines Limited of Canada announced in 1950 its plans to begin preparations for producing nickel from its recently explored reserves in Manitoba.

In early 1951 it was decided by the United States government to rehabilitate the nickel producing facilities in Cuba, which had been idle for the previous four years, and resume production. The output from the facility was designated for replenishing United States government stockpiles. Production of nickel in Cuba resumed in 1952 and a record high level of 13,844 short tons was produced in the following year. Additional capacity was still being installed and exploration of other deposits was increased. Record levels of nickel were produced in each of the four following years and this trend would have continued if not for the Cuban revolution which began in 1958. By 1960 all nickel companies in Cuba had been nationalized by the new government. Production has continued under the new regime, though few details of the industry are available. While New Caledonia and the U.S.S.R. expanded production quite a bit, and several other countries began to produce nickel, the shortages continued in the industry up to the second half of 1957.

During this period no fewer than ten additional countries began producing nickel, though the most important producers remained Canada, New Caledonia, the U.S.S.R., and Cuba. Canada still managed to retain almost 60 percent of the market in 1957. Further, a great deal of exploration for viable nickel deposits was being undertaken in many other countries. By 1958 the shortage situation had reversed itself to such an extent that Inco was forced to cut back on production and operate at about 65 percent of capacity for the last half of the year. Exploration and expansion by other producers still continued during the year and was rewarded by an upturn in demand in 1959.

6. Dominance Lost

In 1960, a record level of 358,000 short tons of nickel was produced in the world. Of this amount, 60 percent came from Canadian producers. Throughout the 1960's the U.S.S.R. was the second largest producer of nickel, supplying about 20 percent of the world's nickel, yet it had very little influence on events in the industry. The reason for this was partly due to Canada's dominant position but to a greater extent was due to the fact that up to this time only a small amount, if any, of the nickel produced in the U.S.S.R. ever left the country. It did import some nickel from the free world, but this soon stopped once it was able to obtain a steady supply from Cuba following the revolution there.

The year 1960 was also distinguished by a high level of exploration for new sources of nickel, development of existing deposits, and research to find new markets for nickel. In a real sense, world nickel markets were segregated into the non-communist and communist block consumers. Considering only the non-communist world, the United States was the largest nickel consumer using 49 percent of all nickel available to the free world in 1965. Europe, an area where the use of nickel had been growing throughout the 1950's, accounted for 38 percent of consumption. Japan consumed only 8 percent and various other countries the remainder of the free world nickel supply. Of the nickel supplied from non-communist block producers over 75 percent came from Canada. New Caledonia remained the second largest free world producer though it too had very little influence on the market.

During this period of time Inco maintained virtual control over the market price of nickel. Inco published, on a regular basis, a list of prices for the various types of nickel it produced. The price was quoted in United States dollars, the terms were f.o.b. the refinery, and it was referred to as the producer price of nickel. United States dollars were used since it was the largest consumer of nickel at the time and since dollars were readily acceptable for international trade. Other nickel producers, such as Societe Le Nickel, charged a price which was based on the Inco price, other considerations such as transportation costs and quality being taken into account. Inco allowed the other firms in the industry to supply as much as they could at the set price and then provided for any unmet demand in the market. For many years the "unmet" demand supplied by Inco was the major portion of all nickel consumed.[10]

It appears that at this time Inco determined the price it set on a cost plus mark up basis. That is, a reasonable estimate of the cost of producing a certain type of nickel was derived, to which was added a percentage mark up to cover the cost of exploration, research, and development and to provide for an acceptable return. This price had little relationship with the existing supply and demand conditions in the industry at the time, it generally remained unchanged during periods of shortage or surplus of nickel in the industry. Inco, in a sense, could have been described as a supplier of last resort. In periods of over supply Inco responded by cutting

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[10]The role of Inco as a price leader in the industry is explained in Elizabeth Urquhart (1978), pp. 114-118.

back on production and building up its inventories in an effort to maintain price. When there were shortages in the market, instead of raising price, Inco would increase its rate of production and sell off any accumulated inventory. Several reasons surface as to why Inco would follow such a strategy. Since the demand for nickel is derived from the demand for final products made with nickel, the short run demand for nickel is relatively inelastic. Further, there are few good substitutes for nickel and the cost of nickel is only a small part of the final cost of a typical product. Together, these considerations imply that a price cut will not increase the quantity demanded of nickel to any great extent. Inco has also resisted increasing the price of nickel during periods of shortages, choosing instead to sell nickel from its inventories when possible. This has led to several instances where nickel has been sold on a "black market", at prices significantly above Inco's producer price. Overall, this action has helped contribute to relatively stable prices throughout the time period.

Inco, which was also the world leader in exploration and research, spent a great deal of money on exploration in Ontario and Manitoba, Canada, as well as in other parts of the world, and committed additional money to expanding production at its existing mines and smelters. As it had since its earliest years, Inco continued with a high level of expenditures on the research and development of new products and processes throughout the 1960's. One result of this work was the continued growth in demand experienced during this time period. Inco introduced several new nickel alloys which were well

received for applications requiring ultra-high strength and toughness. These alloys were widely used for aircraft parts and in the aerospace program, two industries experiencing a high rate of growth throughout the time period. The other result of Inco's research during this time was the development of new mining, smelting, and refining processes which both increased productivity and decreased sulphur emissions, a more recent concern. Aside from Inco, Falconbridge and Sherritt Gordon Mines appeared to be the only other companies engaging in this type of activity.

The success of the Canadian companies in developing new markets for nickel did not go unnoticed by the rest of the world. The many years of growth in demand for nickel, along with the periodic shortages of the metal, encouraged an increasing level of exploration and expansion throughout the decade. Societe Le Nickel instituted a plan for the renovation of its facilities in order for it to become a more reliable producer of nickel in the future. The U.S.S.R. continued with steady expansion of its capacity. While the search for nickel touched all parts of the globe, two of the more important areas of exploration and development were in Australia and the Philippines. The development of the Philippine deposits, however, was significantly delayed by the time required by its government to choose a firm to exploit the reserves.

The first Australian nickel deposits were found by prospectors during the gold rush days of the late 19th century and were largely ignored. An evaluation of Australia's nickel prospects was conducted by its Department of National Development, Bureau of Mineral

Resources, Geology and Geophysics in 1962. After the gold tapered off a nickel rush of sorts began that gave new life to the mining activities in Australia and to many of the towns built up during the previous gold rush days.[11] By 1964 several companies had been organized to find and develop the major nickel deposits. The Western Mining Company was one of these and it began systematic exploration of the Kalgoorlie area in September of 1964. After reporting it had located a deposit at Kambalda only the year before, the company commenced producing a small amount of nickel in 1967. It should be noted that some of the infrastructure needed was already built up in some areas from the previous gold and iron mining. The following years would be marked with continious expansion by the Western Mining Company and exploration by other firms. In 1969 the rate of exploration decreased as firms moved toward the development of deposits located in previous years.

By 1970 the Australian nickel industry was moving forward at high speed. Total output had doubled for three consecutive years, with most of this production coming from the Western Mining Company. It had just completed work on a new refinery, and other refineries and smelters were in the planning stage, as were two separate railroad systems. The Western Mining Company finally brought its operations up to full scale production levels in 1976, a full fourteen years after the first steps were taken to enter the industry. At least ten of these years can be attributed to building up the mining

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[11]For an excellent account of the transition from gold mining to nickel mining see Norma King (1972).

facility, smelter, refinery and other support facilities as the deposit was known to be feasible at the latest by 1966. The long period of time required by the Western Mining Company to develop its deposit was not atypical of the nickel industry.

One area in which Inco has had some difficulties is in its relations with organized labor. This has caused some problems for Inco because the extraction of its sulphide ore deposits in Canada required a very labor intensive process. The first major strike against Inco took place in 1958 and lasted about three months. The end result of the strike was a 41 percent reduction in the amount of nickel ore produced and a 29 percent decrease in the amount of finished nickel delivered to its customers. Strikes in 1966 and 1969 had somewhat similar effects on Inco's production levels. While the 1958 strike occurred during a period of excess supply and did not affect the world market for nickel to any great extent, the later strikes both came at a time of high demand and resulted in shortages and higher prices for nickel. They also served to help establish some of the newer nickel producers in the industry and to fuel further exploration and development.

It was partly for this reason that Inco began to search for a suitable laterite type deposit to develop, since less labor was required in the production of such an ore. In fact, extraction of a laterite ore required an energy intensive process, and, with the low cost of fuel at the time, it was believed that the sulphide type deposits would soon lose their importance. One example of this is shown in the development of a nickel deposit in Guatemala by the Iza-

bel Exploration and Mining Company, 80 percent owned by Inco and the remaining share owned by the Hanna Mining Company based in the United States. Exploration first began in 1962 and a site suitable for development was located three years later. Negotiations with the Guatemalan government concerning financial arrangements stalled actual development of the site while plans for the mine and a processing plant were completed in 1969. Some of the work related to road and housing construction, started during the exploration period, did continue. The company and the government came to terms in 1973 and actual construction of the project commenced in the same year. In 1975 it was reported that work on the project had reached the halfway point and that the production of nickel was expected to begin in 1977. Some nickel ore was extracted in 1976 though there were no facilities available to process it. All mining and processing operations had started by the end of 1977, and deliveries of the finished nickel began the following year. Over half of the operating expenses of the Guatemala project went for fuel oil. In 1979 about 7,000 short tons of nickel were produced and this same amount was produced by September of 1980. However, because of the large increases in costs brought about by the situation in the world oil markets, operations were halted in November, and the following year, 1981, the whole facility was mothballed. As of 1984 the project has yet to be reopened. With the higher price for oil, the sulphide deposits quickly regained their importance. Inco, however, would continue to experience strikes from its labor force through the late 1970's and early 1980's.

Other countries involved in exploration during the 1960's were Brazil, the Dominican Republic, Finland, Greece, Peru, Puerto Rico, and Venezuela, to name a few. The result of all of this activity was that the total world production of nickel in 1970 was almost double that produced in 1960. Still, the supply of nickel remained pretty tight through the end of 1974. In retrospect, this period of time, the 1970's, appears to have been a critical turning point for the nickel industry. During these years many of the development and expansionary projects of the late 1950's and 1960's were completed, greatly increasing the amount of nickel available in the 1970's. Further, at about the time that this additional supply began to show up in the market the growth rate in the demand for nickel started to slow down. Previously, the demand for nickel had been growing at about 6 percent per year and many of the producers expected this trend to continue.[12] Around 1975 the growth rate dropped to approximately 2 percent per year and remained at this level for some years to come. Combined, these factors led to a chronic oversupply of nickel for the last half of the 1970's, which carried over into the early 1980's.

The most striking feature of the nickel industry has been the tremendous growth in production experienced over the years. The total amount of nickel produced in 1980 was 14 times as great as that

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[12] The expectation that the trend in the growth of consumption would continue was based on an extrapolitve model of the nickel industry. A more complex model which incorporates the underlying supply and demand structure of the market can be found in C. W. Smithson, G. Anders, Hae-Shin Hwang, and R. D. Martin (1981).

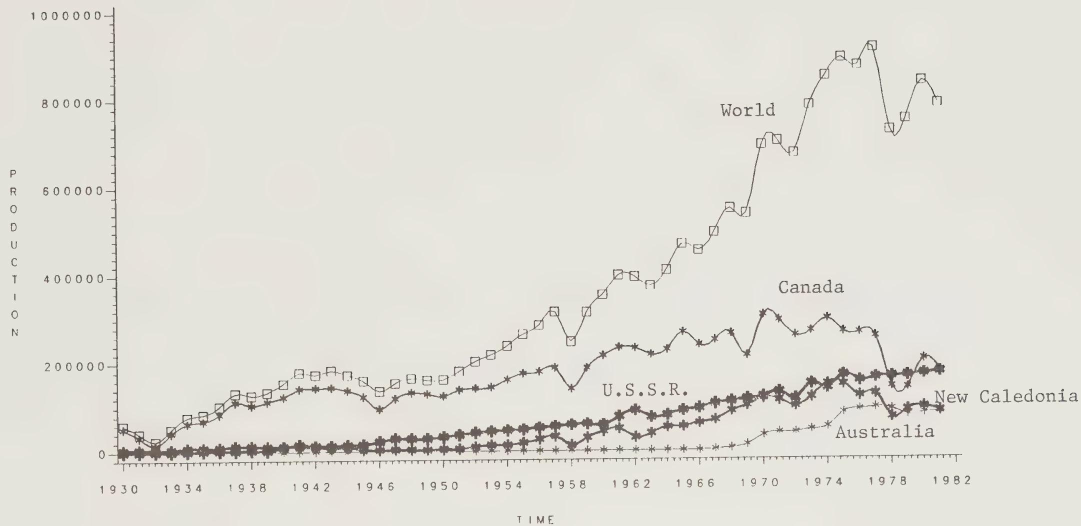

Figure 3.
World Nickel Production: 1930–1981.

in 1930. While a good portion of this came from continuous entry by producers from other countries, in response to the high prices being offered for nickel, Canada certainly contributed its share. In 1930 Canada supplied over 50,000 short tons of nickel, by 1980 this figure had increased more than fourfold to over 200,000 short tons, which was down from its 1974 production level of almost 300,000 short tons. The magnitude of this growth is shown in Figure 3. Pictured is the amount of nickel produced in the world and by several selected countries for the years 1930 through 1981. The growth in demand for nickel can be attributed to several factors: the importance of nickel as an alloy in steel and other metals, the role of nickel in military goods, and the successful research and development by Inco of new products and markets for nickel. While Canada has always been a very important producer of nickel, the U.S.S.R. has in recent years become equally important as far as production levels are concerned.

While the absolute level of Canadian nickel production has certainly been rising over the years, Canada's relative share of production has not. As shown in Figure 4, the percentage of nickel produced by Canada has been steadily declining. Canada's loss in its share of production has been offset by an increasing share going to such countries as Australia, Cuba, the Philippines, and the U.S.S.R. While this change did not occur overnight, the turnabout in shares of production over the course of fifty years has been very dramatic. Whereas a single firm, Inco, produced over 85 per cent of the world's nickel in 1930, by 1982 the largest share of production held by a single country, Canada, was only 23 percent.

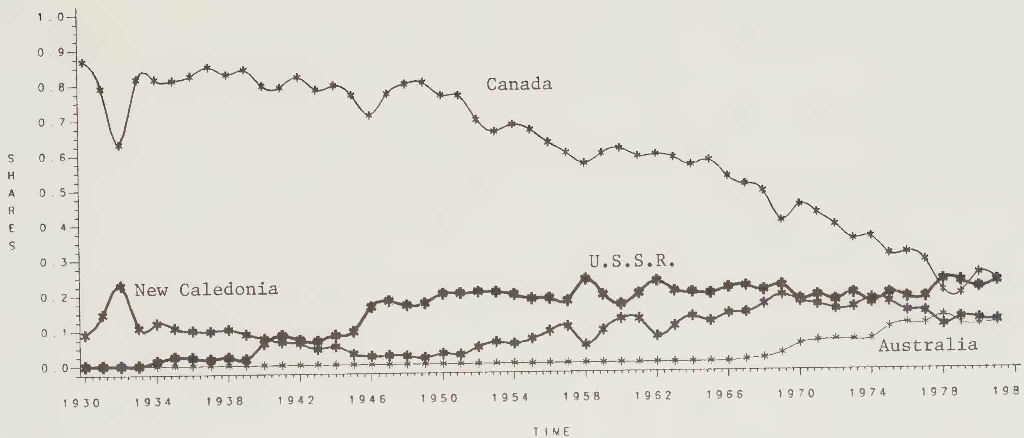

Figure 4.
The Share of Nickel Produced By Country: 1930–1981.

As the share of the nickel market supplied by Inco declined so did its ability to control the price at which it was sold. In the early 1970's Falconbridge several times challenged Inco's role as the industry's price leader. In addition, other firms began to offer discounts on the producer price for nickel sold to such an extent that by July of 1977 Inco discontinued publishing its price list. Inco reinstated the producer price several years later and while some of the specialty nickel produced by Inco is still sold at the producer price, it is not very reflective of the actual selling price for the bulk of nickel exchanged in the market.[13]

The time path of both nominal and real nickel prices are shown in Figure 5. Nickel prices were relatively constant in the earlier time periods, possibly due to Inco's dominance in the market. Inco, at first, was able to set a price which covered its cost of production and a reasonable return on its investment. This price would be changed only periodically, as production costs changed or in response to some long run market trend. In the later years, however, when Inco had lost its dominant position, nickel prices changed much more often in response to short run market trends. That is, in the past Inco could respond to a surplus in the market by building up its inventories of nickel, leaving price unchanged. More recently any surplus of nickel has led to a fall in market prices.

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[13]The manner in which Inco has adjusted its financial structure in response to its changed market position is described in William T. Cannon (1981).

Figure 5.
Nominal and Real Nickel Prices: 1947–1982.

The price of nickel as traded on the London Metal Exchange (L.M.E.) has replaced the producer price as a reasonable indicator of world nickel prices. Nickel was first traded on the L.M.E. in late 1979 with some opposition from the larger producers. Its acceptance grew as the value of nickel traded on the L.M.E. increased and with the realization that the period of Inco's dominance in the industry had passed. Nickel had become more of a world commodity in the sense that no one producer or consumer exerted any great level of influence in the market; price was determined through supply and demand considerations.

Nickel sold on the L.M.E. is delivered by the producer to a designated warehouse. It remains there until sold on the exchange, usually sight unseen. The nickel is sold on a cash only basis and is then transported by the buyer to its final destination. Not all nickel is sold on the L.M.E. and the price charged by a company such as Inco is generally higher than the L.M.E. price. The difference can be attributed to the cost of transportation and any terms of credit extended, as well as some quality considerations. Still, the price will not be very much higher due to the volume of nickel available on the exchange.

The structure of the nickel industry had been slowly changing since the Inco and Mond merger of 1930. Fifty years later the cumulative effect of these changes have produced a drastically different industry. Canada was still the largest producer, providing just under 23 percent of the world's nickel, while the U.S.S.R. was a very close second, producing 22.5 percent of the 1981 supply. Australia,

a relatively recent newcomer to the industry, supplied over 10 percent of the world's nickel, tied with New Caledonia for third place. In addition, Cuba and the Philippines each produced over 5 percent of the nickel supply. On the consumption side, similar changes had taken place. By 1983 the United States was no longer the largest free world consumer of nickel. Consuming 25 percent of the free world nickel supply, it was just barely surpassed by Japan which accounted for 26 percent of the nickel consumed. Europe's share of consumption remained about constant over the past twenty years and was at 39 percent, leaving 10 percent for other free world countries. It is interesting to note that the nickel consumed by the free world no longer was supplied solely by free world producers. The U.S.S.R. and Cuba recently began supplying large amounts of nickel for sale on the L.M.E., an act that was not unprecedented.

In 1967, shortages of nickel due to the 1966 Canadian strikes led to the establishment by some United States consumers of new sources of supply of nickel in several countries, including the U.S.S.R. The United States began to import a small amount of nickel from the U.S.S.R. in 1967 and would continue to do so for a number of years. The amount imported began to increase significantly in 1972 so that by 1974 the U.S.S.R. was the third largest supplier of nickel to the United States. These imports, however, dropped off sharply in 1975 as Australia and the Philippines became established in the industry and as the political situation between the U.S.S.R. and the United States changed. The U.S.S.R. turned to other markets and would soon begin to sell its excess nickel on the London Metal

Exchange. In all a total of twenty-three countries were producing nickel from deposits discovered and developed in the previous thirty years. Most of these nickel producing projects were operating at about 50 percent of capacity because of the over supply of nickel, which was partly due to the world wide recession. Some of the high cost nickel producing facilities were forced to shut down, and price reductions became a common occurrence. An exception to the general trend of reduced output was the U.S.S.R., which continued expanding its capacity and, along with Cuba, began to sell larger quantities on the L.M.E. 31 percent of nickel used in the early 1980's was in stainless and heat resistant alloys, 20 percent in electroplating, 17 percent in heat and corrosion resistant alloys, 11 percent in super-alloys, 10 percent in steel alloys, while other uses consumed the remaining 11 percent.

7. Summary

The nickel industry has undergone many changes since its meager beginnings in the late 18th century. The most striking difference is in the amount of nickel supplied and the number of uses for nickel in the world. While the growth in demand has closely paralleled the increase in the world's output of final goods, much of the growth can be attributed to the efforts of the Canadian nickel producers in searching for new uses of nickel in some of the fastest growing industries. The high rate of increase in demand has encouraged the exploration and development characterizing the industry, resulting in the production of nickel from deposits located all over the world.

Many obstacles of both a technical and physical nature have been faced and overcome in the process. Of particular importance to the present study is the role of a single firm, Inco, in the recent history of the industry.

Inco, at one time, held a virtual monopoly position within the industry. However, its success in developing new markets and new products, along with the importance of nickel in military related products, would eventually bring about a reduction in its share of the market. The entry of other producers into the industry was a lengthy process due to the time involved in locating and developing a nickel deposit. During the period of entry by other firms, Inco played the role of a dominant firm in the industry, cutting back or increasing its production when necessary to maintain the price it had set. To the smaller firms, Inco was more a benefactor than a competitor, making most of its technology available to the industry at large and continually working to insure a growing demand for nickel. Over a period of fifty years the combined effects of entry by other firms and growth in demand have reduced Inco's market share to such an extent that, even though it remains the world's largest nickel producing firm, it no longer has the influence and price setting power it once did in world nickel markets.

The nickel industry can now be described as basically competitive in the sense that no one firm has any real control over the price of nickel. World supply and demand conditions dictate the price, as evidenced by the importance of the London Metal Exchange as one indicator of nickel prices. Another indication of the changes

that the industry has experienced is shown by the chronic surplus of nickel on world markets in the past decade compared to the periodic shortages which characterized its early history. Certainly, a good deal of this is due to the extended downturn in world economies. As was the case after each of the world wars, the nickel industry finds itself at a point where it has a tremendous level of capacity built up but an insufficient number of outlets available to accommodate its production. The only real difference between 1946 and 1984 is that control of the market is no longer in the hands of one company. It remains to be seen which companies, if any, will invest in the research and development in new uses for nickel which are necessary to take up the excess supply available in the market.

CHAPTER IV

THE EVOLUTION OF MARKET STRUCTURE IN A MINERAL RESOURCE INDUSTRY

1. Introduction

The exploitation of an exhaustible natural resource controlled by a monopolist or by a group of competitive firms has been studied extensively since the seminal work of Harold Hotelling (1931). As noted in Chapter II, the effects of uncertainty, exploration, and backstop technologies on market equilibria have been added to the analysis.[1] Futhermore, the focus of study has shifted away from the polar cases of monopoly and competition to the investigation of intermediate industry structures. One area of interest is in markets characterized by a cartel in direct competition with a group of smaller firms as in the oil industry. Existing models that describe such industries predict that market structure will change over time from competition towards monopoly.[2] This result should, however, be considered carefully since the assumption employed concerning the speed of capital adjustments is quite restrictive. That is, the analysis assumes that firms can instantaneously increase the amount of capital utilized. Firms are also assumed to have identical cost functions. Casual empiricism suggests that this is not true for most

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[1] See Robert S. Pindyck (1980), Kenneth J. Arrow and Sheldon Chang (1982), and Partha Dasgupta and Joseph E. Stiglitz (1981) as prime examples of the direction of this analysis.

[2] Stephen W. Salant (1976) and Richard J. Gilbert (1978) via independently developed models of the oil industry, conclude that the OPEC cartel will eventually obtain a monopoly position in the market.

natural resource industries including the oil industry. Further, the history of the nickel industry indicates that the exact opposite can occur; market structure can change over time from virtual domination by a single firm into competition. This is of interest because Stephen W. Salant's (1976) and Richard J. Gilbert's (1978) analysis of price leadership in a nonrenewable resource market predicts exactly the opposite trend in market structure. Thus, under the conditions that characterize the nickel industry, neither Salant's nor Gilbert's predictions hold. If these conditions more accurately describe oil markets than the assumptions embedded in previous analyses, then study of the nickel industry may offer significant insight into the future structure of world oil markets.

A second area of concern centers on the implications of most natural resource models with respect to the trend of prices over time. The theories generally predict that market price less the marginal cost of production should be increasing at an exponential rate.[3] However, empirical tests of various resource industries fail to support such a claim.[4] In general, resource prices have been growing at a rate less than the market interest rate, although the theory predicts that the two rates will be equal. In some cases resource prices have been decreasing over time. This failure to verify the theoretical results implies the need for an extension of the basic

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[3] A notable exception is found in Kenneth J. Arrow and Sheldon Chang (1982) for the case where reserves are distributed randomly and are located through exploration.

[4] See Harold J. Barnett and Chandler Morse (1963), Gerhard Anders, W. Philip Gramm, and S. Charles Maurice (1978), Harold J. Barnett (1979), and Margaret E. Slade (1982).

natural resource model.

The purpose of this Chapter is to present a general model of a nonrenewable natural resource industry dominated by a single firm confronted with potential entry or expansion from a group of smaller firms. The model, described in Section 2, is used to determine the optimal pricing policy of the dominant firm over time and the effect of this policy on the entry and production decisions of the fringe sector. The model is differentiated from previous dominant firm-mineral resource models in that production costs and the size of deposits are allowed to vary across firms. Further, limitations on the ability of firms to expand production quickly are incorporated into the model. The implications of the model when this constraint is not effective are discussed in Section 3. An important result of the model is that under binding constraints on adjusting capacity Hotelling's pricing rule does not hold and market structure is expected to change from monopolistic towards competition. This result will be described in Section 4. Gilbert (1978) has argued that the price of the resource may actually fall while the constraint is binding. The special circumstances under which this result will obtain are presented in Section 5. In Section 6 the effects of growth in market demand are discussed, and in Section 7 the possibility of an unlimited resource stock is addressed.

Due to the intertemporal nature of the problem under consideration, the calculus of variations is employed as an anlytical tool in obtaining a solution to the model. The main text contains only the basic objective functions and equations necessary for the exposition

of the theory. A more formal statement of the problem, as well as the derivations, can be found in the mathematical appendix to this chapter. The interested reader may consult this section as desired, although it is by no means necessary, because all economic interpretations of the model are found in the main text.

2. The Model

The model posits a dominant firm competing with a group of fringe firms in a nonrenewable resource industry. The dominant firm is assumed to exist ex ante but the results can be easily extended to the case where the dominant firm is formed by the merger of two or more smaller firms ex post. It should be noted that whether or not the dominant firm retains its market power over time will depend upon the actions taken by the firm with regard to its pricing policy. The model is general in that it allows for market structures ranging from competition to monopoly. In addition, it incorporates capacity constraints and constraints on the speed of capital adjustments. The model assumes that the firms are extracting a homogeneous, exhaustible resource. This assumption is maintained in order to focus directly on the impact of binding capacity constraints and unequal production costs across firms on the pricing policy of the dominant firm and the time trend in market structure. This assumption can be compared to the case where firms exploit one form of the resource first, then later shift to another technology to extract a different type of ore from which the same resource is obtained. In the case of nickel, this can be compared to the present exploitation of land

based ore reserves. While these deposits may eventually be exhausted, nickel as a resource certainly will not be, it would still be available from the mining of certain types of ore from the ocean floor and via the scrap market. On the other hand, nickel would cease to be a resource with the introduction of a perfect substitute.

It is assumed that there exist two distinct groups of resource owners each with a deposit of known size and differing costs of production. There exists some backstop technology which can be produced at a constant per unit cost $\bar{P}$.[5] The dominant firm, denoted by the subscript d, is endowed with both the largest initial stock of the resource and the lowest production costs. The competitive fringe, denoted by the subscript f, is composed of a group of smaller firms and takes price as given. The fringe sector then seeks to maximize the present value of its discounted cash flow

$$\int_0^T \{P(t)Q_f(t) - C_f(Q_f(t)) - [\delta + r]K_f(t)\}e^{-rt}dt + K_f(0)$$

by choosing the rate of output, $Q_f(t)$, and the level of of the capital stock, $K_f(t)$, in each time period. $C_f(Q_f(t))$ denotes the fringe sector's variable cost function, δ the depreciation rate of capital, and r the market rate of interest. The competitive sector then, simply attemps to obtain the highest return possible from its investment. It is assumed that the marginal production cost of the fringe

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[5]Joseph E. Stiglitz and Partha Dasgupta (1982) show the effect of the backstop technology under various market structures. In the case of nickel, the backstop technology could be nickel from the sea. Gerhard Anders and T. P. Mohide (1980) provide a description of the nature and the impact of such ocean floor mining.

sector, $C_f'(Q_f(t))$, equals some positive constant up to the level of its resource stock; i.e., $C''_f(Q_f(t)) = 0$ for $Q_f(t) \leq S_f(t)$, and $C''_f(Q_f(t)) = \infty$ for $Q_f(t) > S_f(t)$. That is, marginal production costs are constant up to the limit of the remaining reserve and then become infinitely high once the reserve is exhausted.[6] The price of capital is, without loss of generality, assumed to be one. The level of output produced by this sector in each time period is assumed to be limited by the amount of capital in place according to

$$Q_f(t) \leq aK_f(t),$$

where a is a positive constant. One unit of capital can produce, at most, a units of output. It is required that the fringe sector's total production cannot be greater than its beginning stock of the resource, i.e.,

$$\int_o^T Q_f(t)dt \leq S_f(0)$$

where $S_f(0)$ denotes the size of the fringe sector's original resource deposit.

This group of resource owners is not required to begin production in the initial period, i.e., $K_f(0) = \underline{K}_f \geq 0$. For the fringe sector to produce in this period it must either be endowed with some capital, $K_f(0) > 0$, or it must invest in new capital, $\dot{K}_f(0) > 0$. If

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[6]This assumption, following A. Michael Spence (1977) for the case of a typical manufacturing firm facing a capacity constraint, is made to keep the problem tractable. A similar assumption can be found in the analysis of Stephen W. Salant (1976) and Richard J. Gilbert (1978).

the fringe sector has no capital in the initial period, then it considers the time of entry into the industry as a decision variable. It will not enter the industry until price reaches the entry inducing level P_f^{ξ}, i.e., the price at which the fringe sector can earn nonnegative profits. Once the price of the resource reaches P_f^{ξ} the fringe sector invests in capital and begins to produce the resource.[7] The firm remains in the industry until either its reserve is depleted or its capital stock is completely depreciated. It will invest in additional capital stock only if price remains above the value P_f^{ξ}. Formally, the fringe sector seeks to maximize

$$(4.1) \quad \int_o^T \{P(t)Q_f(t) - C_f(Q_f(t)) - [\delta + r]K_f(t)\}e^{-rt}dt + K_f(0) \\ + \mu_f(t)[\alpha K_f(t) - Q_f(t)] \\ + \lambda_f[S_f(0) - \int_o^T Q_f(t)dt]$$

by choosing the level of output, $Q_f(t)$, and capital, $K_f(t)$; where $\mu_f(t)$ and λ_f are the Lagrangian multipliers.[8] A more formal statement of the problem can be found in the mathematical appendix to this chapter.

The first order conditions which maximize (4.1) in each time period for the fringe sector require that it hold no excess capacity over the production period and that the fringe's reserve will be

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[7]The entry inducing price may, in actuality, be different for each firm and will depend on the level of the firm's costs. Following Richard J. Gilbert and Steven M. Goldman (1978), a single price is employed which induces entry into the industry by the fringe sector.

[8]For a discussion of Lagrangian techniques, see Morton I. Kamien and Nancy L. Schwartz (1981).

exhausted by the end of the time horizon. The unconstrained shadow price of capital to the fringe sector can be written as

$$(4.2) \qquad \mu_f(t) = [(\delta + r)/\alpha]e^{-rt}.$$

The equilibrium condition for the fringe sector in each time period is found to be

$$(4.3) \qquad P_n(t) = P(t) - C_f'(Q_f(t)) - (\delta + r)/\alpha = \lambda_f e^{rt}.$$

$P_n(t)$ signifies the net price of the resource; i.e., the market price of the resource less all marginal costs of production. Since marginal cost is assumed to be constant, the optimal level of production may appear to be indeterminant from equation (4.3). In this case, λ_f, the marginal user cost of the resource to the fringe sector, plays an important role in determining the equilibrium value of output, $Q_f^*(t)$. That is, if actual production is less than the optimal level, the marginal user cost of the resource will be lower than that defined by equilibrium and equation (4.3) will not hold. On the other hand, if actual production is greater than the optimal level, the marginal user cost of the resource will be greater than that defined by equilibrium and equation (4.3) will not hold. As output increases in the initial time period, so does the value obtained for the marginal user cost of the resource. The marginal user cost of the resource will adjust then until equilibrium is attained. The equilibrium value of marginal user cost determines the optimal level of production in each time period. This is the level of production for which the market price of the resource less the constant marginal

production cost is equal to the marginal user cost of the resource. The user cost of the resource is defined as the present value of the future profits foregone by a decision to produce a unit of output today.

Ceteris paribus, $Q_f^*(t)$ defines the optimal production response of the fringe sector over time to a given price path. Similarly, $K_f^*(t)$ defines the optimal level of capital held by the fringe sector in each time period for the given price path. Clearly, the fringe sector will invest in additional capital only when its existing capital stock is less than the optimal capital stock; i.e., $K_f(t) < K_f^*(t)$. That is, as long as the actual level of capital stock is below the optimal level, the fringe sector will invest as quickly as possible to achieve its target value, but the adjustment in capacity may take more than one time period to be completed. In all time periods in which $K_f(t) > K_f^*(t)$ the fringe sector will not invest in any additional capital but will attempt to decrease the level of its capital stock. In the present case the fringe sector can instantaneously achieve the desired level of capital stock. While this may be an unrealistic assumption, its implications are developed here so as to be compared to the case when firms are constrained in their ability to increase capital stocks quickly. This possiblity, that the capacity level may have to be built up through investment over successive periods of time, will be discussed in a later section.

The dominant firm, taking the level of production by the fringe sector in each period as given, can determine the series of residual demand curves it faces in the market. That is, market demand,

$Q(P(t))$, less the given fringe production, $Q_f(t)$, equals the dominant firm's residual demand in each time period. The dominant firm, given residual demand, chooses an optimal price path which is supported by the level of its sales. $Q(P(t))$ is the market demand function with $dQ/dP < 0$. The initial capital stock of the dominant firm is strictly positive and greater than that of any individual fringe firm, but not necessarily greater than that of the fringe sector. $\bar{P} = P(T)$ may be viewed as either the choke price of the resource or the price of the backstop technology. A choke price is the price at which the resource in question will no longer be demanded; i.e., $Q(\bar{P}) = 0$. The backstop technology is a resource substitute which is available with a perfectly elastic supply at the price $\bar{P}$. $Q(P(t)) - Q_f(t)$ is the residual demand curve faced by the dominant firm in each time period. In effect, the dominant firm takes as given the production path of the fringe sector and provides the additional output necessary to maintain the price it sets. Formally, the dominant firm seeks to maximize

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\begin{aligned}
(4.4) \qquad & \int_o^T \{P(t)[Q(P(t)) - Q_f(t)] - C_d(Q(P(t)) - Q_f(t)) \\
& \quad - [\delta + r]K_d(t)\}e^{-rt}dt + K_d(0) \\
& \quad + \mu_d\{\alpha K_d(t) - Q(P(t)) + Q_f(t)\} \\
& \quad + \lambda_d[S_d(0) - \int_o^T \{Q(P(t)) - Q_f(t)\}dt]
\end{aligned}
$$

by choosing the level of prices, $P(t)$, and its capital stock, $K_d(t)$, in each time period. Again, a more formal statement of the problem can be found in the appendix.

As in the case of the fringe sector, the first order conditions that maximize (4.4) require that the dominant firm holds zero excess capacity[9] and imply that its reserve will eventually be exhausted. The equilibrium condition obtained for the dominant firm requires that

$$(4.5) \qquad P(t) + \frac{Q(P(t)) - Q_f(t)}{dQ(P(t))/dP(t)} - C_d' - (\delta + r)/a = \lambda_d e^{rt}.$$

The first two terms on the left hand side of (4.5) represent the change in the dominant firm's total revenue with respect to a change in the price of the resource. It includes two effects, that of the change of price on the value of the firm's inframarginal units of output and the effect on the firm's market share. Equilibrium for the dominant firm requires that marginal revenue less the marginal production and the constant capital costs is equated to the firm's marginal user cost of the resource in all periods of positive output. Equation (4.5) can also be written as

$$(4.6) \qquad MR_n(t) = \lambda_d e^{rt},$$

where $MR_n(t)$ denotes the dominant firm's marginal revenue net of all marginal production costs.

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[9]Michael A. Spence (1977) suggests that if the dominant firm is the low cost producer it may hold excess capacity as a threat against the fringe firms. In holding excess capacity, a monopolist could discourage entry by threatening to expand output and charge the limit price if entry does occur. This case will be relevant only when investment by the fringe firms is irreversible.

Condition (4.5) provides insight into the optimal strategy of the dominant firm in a variety of settings. If the competitive sector does not exist, $Q_f(t) = 0$ for all t, then (4.5) reduces to the typical maximization condition for a monopolist in an exhaustible resource industry. If the fringe sector exists but is not producing, $Q_f(t) = 0$, then the dominant firm is a monopolist constrained by potential entry. If the market share of the fringe sector is not very large, $Q_f(t)$ is small relative to $Q(P(t))$, then the dominant firm has some market power and may be viewed as the price leader. If the fringe sector supplies a large portion of the industry, $Q_f(t)$ is large relative to $Q(P(t))$, then the firm in question has little market power and price will be close to the competitive price. In the extreme case, when $Q_f(t)$ approaches $Q(P(t))$, the dominant firm is no longer dominant and behaves as if it were a member of the competitive fringe. The solution to (4.4) yields the optimal pricing path and capacity level of the dominant firm, given the production path of the fringe sector.

It should be obvious at this point that the fringe sector has been modeled as a single firm. In reality, this sector is composed of many heterogeneous firms that enter the industry at various points in time. The assumption of a single firm representing the fringe sector is maintained solely for analytical ease and does not change the results of the analysis compared to the case in which the fringe sector is treated as a collection of distinct, price taking firms.

Ceteris paribus, $P^*(t)$ defines the optimal price path of the dominant firm for a given production path of the competitive sector.

Similarly, $K_d^*(t)$ defines its optimal capital stock. It should be noted that while the price path $P^*(t)$ is optimal for the dominant firm given the production path of the fringe sector, the fringe's production path may now not be optimal given the price path determined by the dominant firm in response to the fringe's original production path. If it is, equilibrium is reached and no further adjustment is necessary. If not, the fringe sector determines a new optimal production path given the price path announced by the dominant firm. Likewise, the original price path determined by the dominant firm may then no longer be optimal given the new production path of the fringe sector. If it is, equilibrium is attained; if not, the dominant firm must determine a new, optimal price path. This adjustment process will continue until a final equilibrium is reached, that is, until the competitive sector can no longer adjust its production path in such a way as to be better off given the price path of the dominant firm, and the dominant firm cannot change the path of prices in any way as to improve its situation given the fringe sector's production path. That such an equilibrium can exist, as well as the conditions under which it will exist, have been shown by Salant (1976). The reader will be alerted in any cases where equilibrium is not guaranteed.

This model, then, can accommodate the existence of a firm with various levels of market power.[10] The actual market structure found in an industry will depend on the relative production costs across

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[10]For a discussion of an oligopolistic exhaustible resource market see Tracy D. Lewis and Richard Schmalensee (1980).

sectors, deposit size, and the speed of capital adjustments. Under general conditions the market structure of the industry will be expected to change over time. Two opposing results are shown to be possible; the industry may evolve from competition into monopoly or from monopoly toward competition. The expected direction of the change can be predicted from the model given a set of initial conditions for the industry and will be shown to depend on whether or not there exist constraints on adjusting capacity for the fringe sector. The implications of nonbinding constraints are developed first, then they will then be compared to the results obtained under the assumption of binding constraints on the adjustment of capital stocks.

3. Nonbinding Adjustment Constraints

The direction of the change in market structure and the trend in resource prices can be determined from the fringe sector's and the dominant firm's equilibrium conditions. Condition (4.3) must hold in all time periods during which the competitive fringe is producing. Differentiation of (4.3) with respect to time yields the fringe sector's equilibrium condition over time

$$\frac{\dot{P}_n(t)}{P_n(t)} = r. \tag{4.7}$$

Thus, for the fringe, market price less the marginal production cost (net price) will grow at a rate equal to the market rate of interest. Net price would not grow faster, because if it did there would be no incentive for the firms to extract the resource. The firms would let

the resource remain in the ground and allow it to appreciate in value. There would never be a time period over which net price grew slower than the rate of interest and any of the fringe's resource stock remained in the ground since it would then be optimal for the firms to deplete the deposit before that time and invest the proceeds from the sale of the resource at the market rate of interest. Hence, there will be some output adjustment by the fringe sector to guarantee that (4.7) will hold.

For all time periods in which the dominant firm is producing, condition (4.6) must hold. Differentiation of (4.6) with respect to time yields the dominant firm's equilibrium condition over time

$$\frac{\dot{MR}_n(t)}{MR_n(t)} = r. \tag{4.8}$$

This implies that marginal revenue less the marginal cost of production and the constant capital costs (net marginal revenue) grows at a rate equal to the market rate of interest. The dominant firm will make some adjustment in the resource price to insure that this rule will hold.

Conditions (4.7) and (4.8) can be used to characterize market equilibria and the path of prices over time. When neither the fringe sector nor the dominant firm is constrained in adjusting its capacity, market equilibrium is similar to that obtained by Salant (1976) and Gilbert (1978). Both net price (for the fringe) and net marginal revenue (for the dominant firm) will grow at the rate of interest over all time periods in which there is a positive level of output

from both sectors. The initial price set by the dominant firm will be below the monopoly price but above the competitive price for the resource.

It has been shown that both net price and net marginal revenue grow at a rate equal to the interest rate while the firms are producing. However, at the time when the dominant firm sells its last unit of the resource its net price will just equal its net marginal revenue. This implies that over some period of time either net marginal revenue must grow at a rate greater than the market rate of interest or net price must be increasing at a rate less than the discount rate. The first possibility can be ruled out since if there was a period of time during which net marginal revenue was growing faster than the rate of interest the dominant firm would be better off by withholding its output from the market until after this period had passed. The latter circumstance can occur if either the dominant firm is an unconstrained monopolist over the relevant time horizon or if the fringe sector has exhausted its reserves by this time. Assuming that the competitive fringe does exist, there must be a period of time over which both sectors are producing and both net price and net marginal revenue are growing at a rate equal to the rate of interest. The fringe sector is induced to shift its production towards earlier time periods in order to take advantage of the higher than competitive price set by the dominant firm. The dominant firm, on the other hand, must restrict its output in order to maintain the price it sets, conserving its deposit for a later date. At some time, t^*, the fringe sector will have exhausted its resource stock and the dominant

firm will enjoy monopoly status in the industry for the remainder of the time horizon.

Now, in order to focus attention more closely on the impact of the difference in capacity costs and capacity adjustment constraints across sectors, it will be assumed for the remainder of the analysis that the variable production costs are zero for both sectors, which implies then that $C_f'(t) = C_d'(t) = 0$.[11] In this case, the unconstrained fringe sector equilibrium condition (4.3) can be written as

$$P(t) = (\delta + r)/a + \lambda_f e^{rt}. \tag{4.9}$$

That is, the market price of the resource will be equal to the fringe sector's capital costs plus its marginal user cost of the resource in equilibrium. Condition (4.9) can be utilized to obtain the modified Hotelling rule for the fringe sector

$$\frac{\dot{P}(t)}{P(t)} = r \left\{ \frac{\lambda_f e^{rt}}{\lambda_f e^{rt} + (\delta + r)/a} \right\} \tag{4.10}$$

where $\dot{P}(t)$ is defined as $dP(t)/dt$.

The reader should note the difference between the two forms of the equivalent equilibrium conditions (4.10) and (4.7). Equation (4.7) shows that the net price of the resource, that is, market price less the marginal production costs, will be growing at a rate equal to the rate of interest over time. On the other hand, (4.10) states

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[11] Stephen W. Salant (1976) and Richard J. Gilbert (1978) show that the various assumptions concerning marginal costs; i.e., constant and identical, increasing and identical, or zero, across sectors will not alter the results of the analysis.

that the market price of the resource will be increasing at a rate less than the interest rate. In fact, in the earlier time periods when the marginal user cost of the resource is small relative to that of the marginal production costs, there may well be only a slight relationship between the rate of change in price and the interest rate. It will only be late in the time horizon, when the marginal user cost of the resource is large relative to the incremental production costs, that the market price of the resource will change at a rate approximately equal to the market interest rate. This is an important distinction since many empirical tests of resource prices over time examine only market prices, due to the lack of adequate cost data.[13] While these studies generally show increasing resource prices, the magnitude of the increase is always less than that of any interest rate.

Similarly, the dominant firm equilibrium condition (4.5) can be written as

$$(4.11) \qquad MR(t) = P(t) + \frac{Q(P(t)) - Q_f(t)}{dQ(P(t))/dP(t)} = (\delta + r)/\alpha + \lambda_d e^{rt}$$

where MR(t) is the marginal revenue function of the dominant firm. Equation (4.11) can also be expressed as

$$(4.12) \qquad MR(t) = P(t)[1 + \gamma_d(t)/\epsilon(t)],$$

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[12]See Harold J. Barnett and Chandler Morse (1963) and Margaret E. Slade (1982).

where $\gamma_d(t)$ is defined as

$$1 \geq \gamma_d(t) \equiv \frac{Q(P(t)) - Q_f(t)}{Q(P(t))} \geq 0,$$

the market share of the dominant firm in period t and $\epsilon(t)$ is defined as

$$0 > \epsilon(t) \equiv \frac{dQ(P(t))\ P(t)}{dP(t)\ Q(P(t))} > -\infty,$$

the elasticity of market demand in period t. Condition (4.11) can be employed to derive the modified pricing rule for the dominant firm

$$\text{(4.13)} \qquad \frac{\dot{M}R(t)}{MR(t)} = r\left\{\frac{\lambda_d e^{rt}}{\lambda_d e^{rt} + (\delta + r)/a}\right\}$$

where $\dot{M}R(t)$ is defined as $dMR(t)/dt$.

Proposition 1: *Under the assumption of nonbinding constraints on the ability of the firms in a nonrenewable resource industry to adjust capacity, a dominant firm, competing with a group of fringe firms, will eventually achieve a monopoly position within the industry.*[13]

Proof:

Utilizing (4.10) and (4.13), the relationship between the rate of change of price for the fringe sector and the rate of change of

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[13]The dominant firm may in reality be a cartel resulting from the merger of two or more smaller firms. The formation of the cartel is due to the incentives any group of firms in a competitive industry may have to collude and take advantage of the market power derived from doing so. See Stephen W. Salant (1976).

marginal revenue for the dominant firm can be defined by

$$\frac{\dot{P}(t)}{P(t)} \gtreqless \frac{M\dot{R}(t)}{MR(t)} \quad \text{as} \quad \lambda_f e^{rt} \gtreqless \lambda_d e^{rt}.$$

In all time periods that the dominant firm has market power, it must be the case that the market price of the resource is greater than its marginal revenue. Therefore, $\lambda_f e^{rt} > \lambda_d e^{rt}$ for all time periods in which that power is exercised and both sectors are producing.[14] Hence it must be the case that

$$\frac{\dot{P}(t)}{P(t)} > \frac{M\dot{R}(t)}{MR(t)} \tag{4.14}$$

i.e., the rate of change of price for the fringe sector must be greater than the rate of change of marginal revenue for the dominant firm. By differentiating (4.12) with respect to time it can also be shown that the rate of change of the dominant firm's marginal revenue is equal to

$$\frac{M\dot{R}(t)}{MR(t)} = \frac{\dot{P}(t)}{P(t)} + \frac{\dot{\gamma}_d(t)/\gamma_d(t) - \dot{\epsilon}(t)/\epsilon(t)}{\epsilon(t)/\gamma_d(t) + 1} \tag{4.15}$$

for $\gamma_d(t) > 0$. Equations (4.14) and (4.15) may now be employed in determining the trend in market structure over time. Equation (4.14)

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[14] This can be shown by comparing (4.9) and (4.11); i.e.,

$$P(t) = (\delta + r)/a + \lambda_f e^{rt} > (\delta + r)/a + \lambda_d e^{rt} = MR(t). \tag{1}$$

By subtracting $(\delta + r)/a$ from both sides of the inequality the result is immediately obtained.

implies that

$$(4.16) \qquad \frac{\dot{\gamma}_d(t)/\gamma_d(t) - \dot{\epsilon}(t)/\epsilon(t)}{\epsilon(t)/\gamma_d(t) + 1} < 0.$$

Since the marginal revenue of the dominant firm and the market price of the resource must both be positive in equilibrium, evaluation of (4.12) shows that the denominator of (4.16) is negative, which then yields

$$(4.17) \qquad \frac{\dot{\gamma}_d(t)}{\gamma_d(t)} > \frac{\dot{\epsilon}(t)}{\epsilon(t)}$$

That is, the rate of change of the dominant firm's market share must be greater than the rate of change of the elasticity of market demand. In addition, $\epsilon(t) < 0$ and $\gamma_d(t) > 0$ imply that the direction of change in the dominant firm's market share, $\dot{\gamma}_d(t)$, will depend on the direction of the change in the elasticity of demand, $\dot{\epsilon}(t)$. If the elasticity of demand is decreasing over time and is greater in absolute value than the dominant firm's market share, $\dot{\epsilon}(t) < 0$ and $|\epsilon(t)| > \gamma_d(t)$, which is Salant's assumption, or if the elasticity of demand is constant over time and market demand is elastic, $\dot{\epsilon}(t) = 0$ and $\epsilon(t) < -1$, which is Gilbert's assumption, then (4.17) implies that the market share of the dominant firm will be constantly increasing over time; i.e., $\dot{\gamma}_d(t) > 0$. On the other hand, when the elasticity of demand is increasing over time, $\dot{\epsilon}(t) > 0$, the direction of the change in the dominant firm's market share is indeterminate. Alternatively, $\dot{\epsilon}(t) \leq 0$ implies that the market share of the competi-

tive fringe will be strictly decreasing over its entire time horizon. As its market share approaches zero, the fringe sector will exhaust its resource stock and the dominant firm will obtain a monopoly position in the industry.[15]

The time paths of price and marginal revenue when the capacity adjustment constraint is nonbinding are shown in Figure 6. During the time period in which both sectors are producing, t an element of $[0,t^*]$, price is increasing at a faster rate than is marginal revenue. For the case where $\dot{\epsilon}(t) < 0$, the market share of the fringe sector is steadily declining over time and by time t^* its reserves are exhausted and its production ceases. For the remainder of the time horizon, t an element of $[t^*,T]$, the dominant firm operates as an unconstrained monopolist in the industry. During this time period the resource price is increasing at a slower rate than is marginal revenue. This result is based on the requirement that for the dominant firm (or the cartel) to be able to increase the price of the resource above the competitive price it must withhold some of its reserve from the market. Conversely, the fringe sector is enticed into producing a larger amount of its resource stock in the earlier time periods. The fringe sector produces so much more of its

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[15]Once the fringe sector has exited the industry the rate of change of marginal revenue will be defined by

$$\text{(1)} \qquad \frac{M\dot{R}(t)}{MR(t)} = \frac{\dot{P}(t)}{P(t)} - \frac{\dot{\epsilon}(t)/\epsilon(t)}{\epsilon(t) + 1}.$$

where $0 > \epsilon(t) > -1$. From this point on $\dot{P}(t)/P(t) \gtreqless M\dot{R}(t)/MR(t)$ as $\dot{\epsilon}(t) \gtreqless 0$.

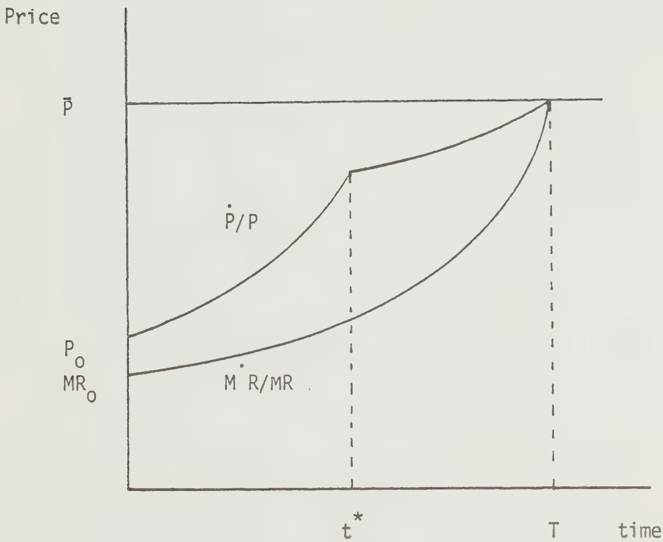

Figure 6.
The Rate of Change of Price and Marginal Revenue: Nonbinding Constraints.

deposit, and the dominant firm conserves on its reserve to such an extent, that the fringe exhausts its reserve at an earlier date than in the competitive solution leaving the dominant firm in complete control of the market.

4. Binding Adjustment Constraints

An additional constraint on the fringe may limit the rate at which it can adjust the size of its capital stock. That is, investment in capital can be both irreversible and time consuming. Thus when capital has no value in secondary markets the stock of capital can decline, at most, at the rate of depreciation. In addition, the time required to install new capacity may restrict the rate at which firms expand. This constraint is assumed to be of the form

$$(4.18) \qquad -\psi_f(K_f(t)) - \delta K_f(t) \le \dot{K}_f(t) \le \phi_f(K_f(t)) - \delta K_f(t),$$

where ϕ_f is the upper bound on the rate at which new capital can be brought on line and ψ_f is the upper bound on the rate at which capital can be sold off. Both are assumed to be related to the level of the existing capital stock. The more capital firms in the fringe sector command, the easier it is to expand further and the harder it is to dispose of capital; i.e., $\psi_f' \equiv d\psi_f/dK_f < 0$, and $\phi_f' \equiv d\phi_f/K_f > 0$, the rate of change of the respective constraints with respect to the existing level of the capital stock.

The interesting case concerning changes in market structure over time arises when the constraint on adjusting capacity (4.18) is binding for the fringe sector. Recall the unconstrained equilibrium con-

dition (4.9) for the fringe sector

$$P(t) = (\delta + r)/a + \lambda_f e^{rt}.$$

Now, given that when the constraint on increasing capacity is binding less output will be available in any given time period compared to the unconstrained case, the price of the resource must be higher in the constrained case than in the unconstrained case. Similarly, the marginal user cost of the resource must be smaller in the constrained case than in the unconstrained case since there will be a larger reserve available in any future time period. Further, since the fringe sector has less capital available than is optimal while the constraint is binding, it necessarily follows that the shadow price of capital must be higher in the constrained case than in the unconstrained case. This implies that the problem must be reformulated so that the price of the resource, the marginal user cost of the resource, and the shadow price of capital for the fringe sector can adjust in order to achieve equilibrium.

When the constraint on adjusting capital (4.18) is binding for the fringe sector when increasing, but not when decreasing,[16] the level of capacity, the capital-output relationship becomes[17]

$$Q_f(\tau) \leq a[K_f(0) + \int_0^\tau \{\phi_f(K_f(t)) - \delta K_f(t)\}dt],$$

[16]For a discussion of the case where investment in capital is also irreversible, see Philip J. Mizzi and Steven N. Wiggins (1984).

[17]The relationship is derived in the appendix to this chapter, where a more formal statement of the constrained maximization problem and first order conditions are also found.

In all periods for which the constraint on increasing capacity is binding the fringe seeks to maximize

$$(4.19) \qquad \int_0^{\tau} \{P^c(t)Q_f(t) - [\delta + r]K_f(t)\}e^{-rt}dt + K_f(0)$$
$$+ \mu_f^c(t)[\alpha[K_f(0) + \int_0^{\tau}\{\phi_f(K_f(t)) - \delta K_f(t)\}dt] - Q_f(t)]$$
$$+ \lambda_f^c[S_f^{\tau}(0) - \int_0^{\tau} Q_f(t)dt]$$

where, again to focus attention on the difference in the shadow price of capital across sectors, it is assumed that the variable costs of production are zero. τ defines the time period at which the constraint is overcome by the fringe sector. $S_f^{\tau}(0)$ then, is the amount of the resource stock that must be extracted by the fringe sector before the constraint is no longer binding. The superscript c denotes the values of the term while the constraint on increasing capacity is binding for the fringe sector. $P^c(t)$ then, is the optimal price determined by the dominant firm given the fringe sector's constrained production path. The first order conditions which maximize (4.19) in each time period require that the fringe sector holds no excess capacity and that it will exhaust the required amount of its reserve by the time the constraint is overcome. The solution to (4.19) also yields the constrained shadow price of capital to the firm

$$(4.20) \qquad \mu_f^c(t) = [(\delta + r)/\alpha(\phi_f' - \delta)]e^{-rt}.$$

It must be the case that the unconstrained shadow price of capital be strictly less than the constrained shadow price of capital, since capital is more valuable to the fringe sector while the constraint is

binding. Comparing (4.2), the unconstrained shadow price of capital, with (4.20) implies that

$$(4.21) \qquad 1 > \phi_f' - \delta > 0,$$

where $\phi_f' - \delta$ represents the rate of change of the constrained capital stock held by the competitive sector. The requirement (4.21) is reasonable since $\phi_f' - \delta \leq 0$ implies that the capital stock could never increase over time. Also, $1 > \phi_f' - \delta$ requires that the capital stock cannot double over any one time period. Finally, the equilibrium condition for the fringe sector over all time periods while the constraint on increasing capacity is binding is defined by

$$(4.22) \qquad P^c(t) = [(\delta + r)/\alpha(\phi_f' - \delta)] + \lambda_f^c e^{rt}.$$

Equation (4.22) implies that the constrained market price of the resource is equal to the constrained shadow price of capital plus the constrained marginal user cost of the resource for the fringe sector in equilibrium. $P^c(t)$ is the optimal price path of the dominant firm when the capacity adjustment constraint is binding for the fringe sector. As argued above it must be the case that

$$(4.23) \qquad P(0) < P^c(0), \text{ and } \lambda_f e^{rt} > \lambda_f^c e^{rt}.$$

That is, the constrained initial price of the resource is greater than the unconstrained, since less of the resource will be available in any given time period due to the constraint on the availability of capital; the unconstrained marginal user cost of the resource must be greater than the constrained marginal user cost, since a smaller

amount of the reserve will be depleted in any given time period. Differentiating the constrained fringe equilibrium condition (4.22) with respect to time, and, assuming $\phi_f'' = 0$, yields

$$(4.24) \qquad \frac{\dot{P}^c(t)}{P^c(t)} = r \left\{ \frac{\lambda_f^c e^{rt}}{\lambda_f^c e^{rt} + (\delta + r)/\alpha(\phi_f' - \delta)} \right\}$$

To determine the effect of the constraint on market prices over time the unconstrained rate of change of price (4.10) can be compared with the constrained rate of change of price (4.24).

Proposition 2: *The rate of change of price, $\dot{P}(t)/P(t)$, will be greater in the case of nonbinding constraints on adjusting capacity, than the rate of change of the constrained price, $\dot{P}^c(t)/P^c(t)$, for the case of binding constraints on increasing capacity for the fringe sector.*

Proof:

Utilizing (4.10) and (4.24), it can be shown that

$$(4.25) \qquad \frac{\dot{P}(t)}{P(t)} \gtreqless \frac{\dot{P}^c(t)}{P^c(t)} \quad \text{as} \quad \frac{\lambda_f e^{rt}}{\lambda_f^c e^{rt}} \gtreqless \phi_f' - \delta$$

Inequality (4.21) states the requirement that $1 > \phi_f' - \delta > 0$ for the problem to be economically feasible. By (4.23), the unconstrained marginal user cost of the resource must be greater than the constrained marginal user cost, which implies then that the ratio of the two, $\lambda_f e^{rt}/\lambda_f^c e^{rt}$, is greater than one. From (4.21), (4.25), and the

result that $\lambda_f e^{rt}/\lambda_f^c e^{rt} > 0$, it immediately follows that

$$\frac{\dot{P}(t)}{P(t)} > \frac{\dot{P}^c(t)}{P^c(t)}$$

i.e., price will increase at a slower rate in the constrained case than in the unconstrained case.

Proposition 3: *The unconstrained and the constrained price paths must cross.*

Proof:

Assume the price paths do not cross; then the path of prices over time would be as in Figure 7. If they do not cross, then the constraint is no longer binding at some point t^o before the paths cross. While t is in the range $[0,t^o]$ output is strictly less in the constrained case, and while t is in the range $[t^o,t']$ output cannot be greater than in the unconstrained case. This implies that if the price paths do not cross and the adjustment constraint is binding, the reserve will not be completely exhausted in time period t'. Since this is not optimal from the firm's point of view, it must be the case that the two price paths cross. Hence, either the constraint is binding over the entire time horizon or the constraint is no longer binding at some point after the two price paths cross. When the constraint is no longer binding the equilibrium condition for the fringe sector becomes

$$P^c(t) = (\delta + r)/a + \lambda_f^c e^{rt}$$

Since $\lambda_f e^{rt} > \lambda_f^c e^{rt}$ and by comparing the above equilibrium condition with (4.9), it must be the case that $P(t) > P^c(t)$ after the con-

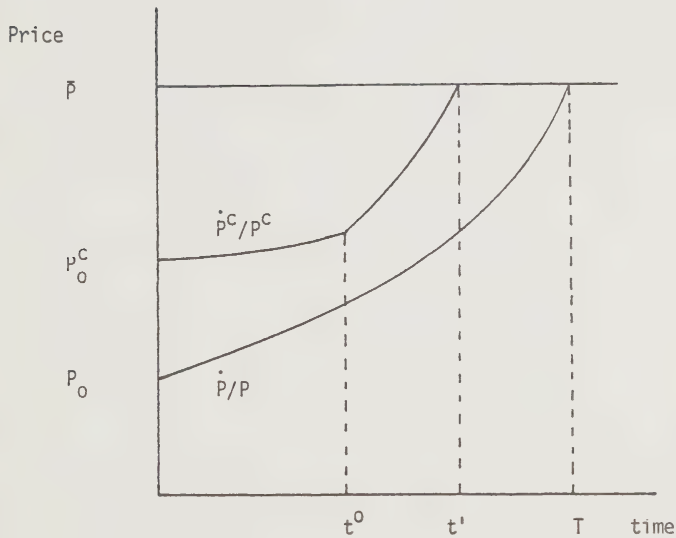

Figure 7.
Comparing the Rate of Change of Price in the Constrained to the Unconstrained Case.

straint on adjusting capital has been overcome.

Consider the case in which the dominant firm has a substantial level of capacity at its disposal and does not have any constraint on adjusting that capacity. Assume further that the competitive fringe has only a small amount of capacity in place and is constrained in increasing its capital stock. In the previous case, the dominant firm set a price for the resource that encouraged expansion by the fringe sector. Since these firms faced no adjustment constraints, the dominant firm sacrificed its market share in the early time periods in order to obtain a higher market share in the later time periods. If a long period of time is required for the fringe sector to expand capacity, it will again be optimal for the dominant firm to choose a high price for the resource. This will encourage entry and expansion in the industry but it may take a relatively long period of time before the additional capacity has any substantial impact on the dominant firm's market share. The level of market power retained by the dominant firm once the constraints have been overcome by the fringe sector will depend on the size of the competitive fringe's reserves, the degree of the constraint faced by the fringe sector, and the level of entry encouraged by the price set by the dominant firm.

When the constraint on adjusting capacity for the fringe sector is sufficiently binding, the initial price set by the dominant firm will be at or near the monopoly price. How far the resource price will be below the monopoly price will depend on the amount of existing fringe capacity in the initial time period. A high price for the

resource will encourage the competitive sector to expand capacity as quickly as is possible given the adjustment constraint.

The fringe sector, in a sense, is forced to conserve on its resource stock at the begining of the time horizon because the capital necessary for production is simply not available. With little or no output from the fringe sector, the dominant firm will take advantage of the high market price for the resource by shifting its production towards the early time periods. If the fringe sector is constrained for a sufficiently long period of time, and the high price encourages a large amount of entry into the industry, the dominant firm may find itself with little market power towards the end of the time horizon.

Proposition 4: *Under sufficiently binding constraints on increasing capacity for the fringe sector market structure is expected to change over time from monopolistic into a dominant firm competing with a group of smaller firms and finally towards competition.*

Proof:

A single firm will eventually lose its monopoly position if $Q_f^*(t) > 0$ for some $P < \bar{P}$; i.e., if the fringe sector finds it profitable to exploit its reserves at some price set by the monopolist. If $Q_f^*(t) = 0$ for all t, the fringe sector is nonexistent and the dominant firm enjoys a monopoly position over the entire time horizon.

Assuming that the competitive sector does exist, the equilibrium condition for the unconstrained dominant firm while the fringe sector is constrained in increasing capacity may be written as

$$MR^c(t) = P^c(t) + \frac{Q(P^c(t)) - Q_f^c(t)}{dQ(P^c(t))/dP^c(t)} = (\delta + r)/a + \lambda_d^c e^{rt}$$

That is, marginal revenue for the dominant firm while the fringe sector is constrained is equal to the firm's shadow price of capital plus its marginal user cost of the resource. This equilibrium condition can be employed to derive the modified marginal revenue rule for the dominant firm while the fringe sector operates under binding constraints on increasing capacity

$$(4.26) \qquad \frac{M\dot{R}^c(t)}{MR^c(t)} = r\left\{ \frac{\lambda_d^c e^{rt}}{\lambda_d^c e^{rt} + (\delta + r)/a} \right\}$$

Utilizing (4.24) and (4.26), the relationship between the rate of change of the resource price and the rate of change of marginal revenue is defined by

$$(4.27) \qquad \frac{\dot{P}^c(t)}{P^c(t)} \gtreqless \frac{M\dot{R}^c(t)}{MR^c(t)} \quad \text{as} \quad \lambda_f^c e^{rt}[\phi_f' - \delta] \gtreqless \lambda_d^c e^{rt}$$

while the constraint is binding for the fringe sector. A necessary condition for Proposition 4 to hold is that the marginal user cost of the resource for the fringe sector be less than or equal to the marginal user cost of the resource to the dominant firm when the fringe sector is constrained in its ability to increase its capital stock; that is

$$(4.28) \qquad \lambda_f^c e^{rt} \leq \lambda_d^c e^{rt}.$$

Equation (4.28) requires that the effect of the constraint is to

shift the burden of supplying the bulk of the market to the dominant firm in the earlier time periods. Since the dominant firm is producing more in the beginning periods than if the constraint was not binding, its constrained marginal user cost of the resource must be greater than its unconstrained marginal user cost; i.e., $\lambda_d^c e^{rt} > \lambda_d e^{rt}$. The constrained fringe, on the other hand, is producing less, so its marginal user cost will be lower than in the unconstrained case. In other words, the net effect of the constraint must be to lower the marginal user cost of the resource to the fringe sector to or below that of the dominant firm. It is easily shown by (4.27) that (4.28) is a sufficient condition for the rate of change of the constrained resource price to be less than the rate of change of the marginal revenue of the dominant firm. If (4.28) holds, $\dot{P}^c(t)/P^c(t) < \dot{MR}^c(t)/MR^c(t)$, from which it can be shown that the inequality in (4.17), the relationship between the rate of change in market share for the dominant firm and that of the elasticity of demand, is reversed; i.e.,

$$\frac{\dot{\gamma}_d^c(t)}{\gamma_d^c(t)} < \frac{\dot{\epsilon}^c(t)}{\epsilon^c(t)}$$

If the elasticity of market demand is constant over time and is greater in absolute value than the dominant firm's market share, $\dot{\epsilon}^c(t) = 0$ and $|\epsilon^c(t)| > \dot{\gamma}_d^c(t)$ which is Gilbert's assumption, or if the elasticity of market demand is increasing over time, $\dot{\epsilon}^c(t) > 0$, then the above relationship implies that the market share of the dominant firm will be decreasing over time while the constraint is bind-

ing; i.e., $\dot{\gamma}_d^c(t) < 0$. For $\dot{\epsilon}^c(t) < 0$, Salant's assumption, the direction of the change in market structure is indeterminate. Once the constraint is overcome, the dominant firm perceives its market share as being so small relative to that of the fringe sector that it is no longer able to influence the industry; it begins to behave as if it were a member of the competitive fringe. From this point on there will be no significant difference between the market price of the resource and the dominant firm's marginal revenue. This implies that the rate of change of the resource price is approximately equal to the rate of change of marginal revenue for the remainder of the time horizon and the industry retains its competitive structure.[18] The case where $\dot{\epsilon}^c(t) \geq 0$ is shown graphically in Figure 8. While the constraint is binding during the time period $[0,t^c]$, $\dot{P}^c(t)/P^c(t)$ <

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[18] Given (4.28), the relationship between market price and marginal revenue for the dominant firm once the constraint is overcome is defined by

$$(1) \qquad P^c(t) = (\delta + r)/a + \lambda_f^c e^{rt} \leq (\delta + r)/a + \lambda_d^c e^{rt} = MR^c(t).$$

Since the marginal revenue of the dominant firm could never be greater than price (this implies a negative market share for the dominant firm), $\lambda_f^c e^{rt} < \lambda_d^c e^{rt}$ implies that the dominant firm will exhaust its resource stock and exit the industry at the same time that the fringe sector overcomes the capacity adjustment constraint. If the dominant firm remains in the industry then, it must be the case that $\lambda_f^c e^{rt} = \lambda_d^c e^{rt}$, so that when the constraint is overcome

$$(2) \qquad P^c(t) = (\delta + r)/a + \lambda_f^c e^{rt} = (\delta + r)/a + \lambda_d^c e^{rt} = MR^c(t).$$

Condition (2) implies that the market share of the dominant firm is so small that the firm is no longer dominant, it operates as if it were a member of the competitive fringe. Additionally, once the constraint has been overcome the relationship between the rate of change of the resource price and that of marginal revenue will be defined by

$$(3) \qquad \dot{P}^c(t)/P^c(t) \gtreqless M\dot{R}^c(t)/MR^c(t) \quad \text{as} \quad \lambda_f^c e^{rt} \gtreqless \lambda_d^c e^{rt}$$

$\dot{MR}^c(t)/MR^c(t)$ and the market share of the dominant firm is falling. The constraint is not overcome until the market power of the dominant firm has eroded to such an extent that at time t^c the industry is basically competitive. It continues as such for the remainder of the time horizon. During this period the resource price and marginal revenue for the dominant firm, as long as it remains in the industry, will be increasing at the same rate.

This result is motivated by the fact that while the competitive sector is constrained in the amount of the resource it can produce, the dominant firm is not. The dominant firm subsequently sets a high price for the resource in the earlier time periods and also produces a greater quantity of its reserve. The fringe sector expands as rapidly as is possible in response to the high resource price, but by the time it has sufficient capacity in place to take advantage of this price, the dominant firm has extracted so much of its reserve that it is not concerned about its lost market share. This does not necessarily imply that the remaining resource stock held by the dominant firm is small. Depending on the level of its initial stock, the amount of the dominant firm's reserve remaining once the fringe sector overcomes the constraint could be very large or may even be exhausted. It is, however, relatively small compared to the remaining stock of the resource held by the fringe sector.

Given (4.28) then, once the constraint has been overcome the two rates of change are equal.

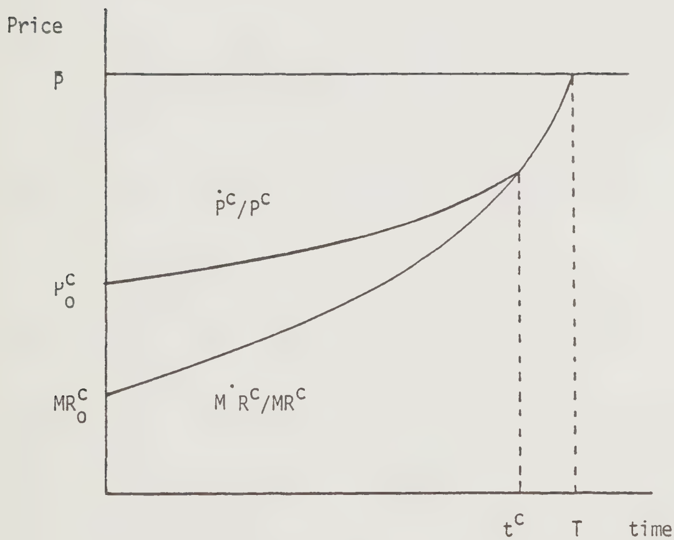

Figure 8.
The Rate of Change of Price and Marginal Revenue: Binding Constraints.

This is a major extension of the natural resource literature characterizing market structures between monopoly and competition. The existing theory, as exemplified by the work of Salant (1976) and Gilbert (1978), implies that the dominant firm will outlast the other producers in the industry. This result depends critically on the assumptions that the dominant firm has reserves and costs similar to that of the competitive fringe and that the speed of capital adjustment by the fringe sector is instantaneous. In general, resource markets are characterized by sharply heterogeneous deposits and the expansion of capacity requires time consuming exploration and development activities. In this setting the variety of behavior that can be optimal is significantly enriched. In particular, if the delay in development is sufficiently long, the optimal strategy will be for the dominant firm to engage in a pricing policy that will lead to the erosion of its dominance over time. Further, it would appear on the basis of casual empiricism that this case has substantial relevance. Not only do we observe a market structure that has evolved from monopolistic to competitive in the nickel industry, but it would also appear that the oil industry is undergoing a similar transformation as OPEC's high price has lead to entry and a dwindling market share over time.

5. Falling Resource Prices

Aside from the question of the trend in market structure, the history of prices in the aluminum and copper industries suggests that resource prices can be decreasing over time. This possibility can be

shown to hold as a special case of the present model.

Proposition 5: *Under certain conditions the price of the resource may be expected to decrease over time.*

Proof:

When ϕ_f'' is nonzero, differentiation of the constrained fringe equilibrium condition (4.22) with respect to time yields

$$\frac{\dot{P}^c(t)}{P^c(t)} = r \left\{ \frac{\lambda_f^c e^{rt} - \phi_f''(\delta + r)/\alpha[\phi_f' - \delta]^2}{\lambda_f^c e^{rt} + (\delta + r)/\alpha[\phi_f' - \delta]} \right\} \tag{4.29}$$

For $\phi_f'' < 0$, equation (4.29) implies that the rate of change of the resource price will be nonnegative. On the other hand, if $\phi_f'' > 0$, and sufficiently large, equation (4.29) implies that the rate of change of the resource price will be negative, and the price of the resource will be falling over time. An increasing rate of change of the capital stock, $\phi_f'' > 0$, implies that the fringe sector will be able to quickly overcome any constraints on adjusting capacity. If the existing capacity of the fringe sector is small in the initial time period, the dominant firm may set a price for the resource near the monopoly price. This will encourage rapid growth in fringe firm capacity and as the additional output becomes available it may drive the market price of the resource down.[19] In the case where the constraint is not binding; i.e., $\phi_f'' = \infty$, the initial price set for the resource will be the competitive price.

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[19]Richard J. Gilbert (1978) provides the basic intuition for the decrease in resource prices when the constraint on increasing capacity is binding for the fringe sector.

6. Growth in Market Demand

The nickel industry has experienced a steady growth in demand, aside from some short-run declines, throughout its history. This growth can be attributed to two factors, the importance of nickel in the production of military hardware and the efforts of Inco and other Canadian producers in the research and development of new products and markets for nickel. One area of concern, then, is the effect of growth in market demand on the results obtained above. Consider the instance where demand is growing at some constant rate over time, i.e.,

$$Q(P,t) = Q(P(t))e^{\eta t}$$

where η is some positive constant equal to the rate of growth in demand. Examination of the fringe sector's maximization problem (4.1) reveals that growth will not affect these firms directly, in that the fringe is motivated solely by the prices offered in the market. Growth in demand may lead to a higher initial market price, but equilibrium still requires that the price increases at a rate equal to the rate of interest when the fringe is unconstrained in adjusting capacity. Net price may increase at a slower rate if the constraints are binding.

On the other hand, market demand enters explicitly into the dominant firm's maximization problem. Incorporating the growing demand function into the dominant firm's maximization problem (4.4), as shown in the appendix, and solving from the first order conditions yields

$$P(t) + \frac{Q(P(t))e^{\eta t} - Q_f(t)}{[dQ(P(t))/dP(t)]e^{\eta t}} - C_d' - (\delta + r)/a = \lambda_d e^{rt}.$$

This equation gives the dominant firm's equilibrium condition for the case of growth in market demand. Equilibrium for the dominant firm requires that the change in total revenue with respect to a change in price less the marginal production costs is equated to the firm's marginal user cost of the resource in all periods of positive output. Differentiation of the equilibrium condition with respect to time yields

$$\frac{\dot{MR}_n(t,\eta)}{MR_n(t,\eta)} = r. \tag{4.30}$$

Equation (4.30) requires that net marginal revenue also grows at the rate of interest over time when market demand is growing. Together, (4.7), the unconstrained rate of change in net price over time for the fringe sector, and (4.30) imply that growth in market demand will not affect the outcome of market structure when adjustment constraints are nonbinding, though it may lead to one or both of the sectors exhausting its resource stock at an earlier date than in the case of zero growth. Similarly, when the fringe sector is constrained in adjusting capacity the direction of change in market structure is not expected to be altered. Growth in demand may, however, extend the time period over which the dominant firm has market power.

The dominant firm may choose between a high price for the resource, which encourages entry into the industry with its resultant

effect on market share, or it may set a low price which does not encourage entry but implies a lower return on the firm's investment. The firm, however, is not limited to only these two options. A third possibility is that the dominant firm sets a very high price for the resource, which encourages entry but also yields a high level of profits for the dominant firm. The firm then reinvests these profits in research and development for new products and new markets for the resource. If the constraint on increasing capacity is binding for the smaller firms, the fringe sector will be expanding as quickly as is possible to take advantage of the high price. It may then be the case that even though the market share of the dominant firm is declining over time, the size of the market may be increasing at such a rate that the dominant firm's absolute level of production of the resource may also be rising. As long as demand keeps increasing, the fringe firms will continue to view the dominant firm as the industry leader.

7. Infinite Resource Stocks

A final area of concern is in the case of a dominant firm with such a large resource stock it can treat its reserve as inexhaustible,[20] while the fringe sector is restricted to have a finite deposit.[21] This is simply a special case of the problem presented

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[20]Industry officials make the claim that Inco can operates as if its deposit is limitless. This may be reasonable, at least for any relevant time horizon, since the proven ore reserves of Inco more than doubled in the forty year period between 1930 and 1970.

[21]For a discussion of the case where all firms have an inexhaustible deposit see Darius W. Gaskins Jr. (1971).

above where the constraint on total production is nonbinding for the dominant firm. The fringe maximization problem would remain unchanged, as would its equilibrium condition, while equilibrium for the dominant firm, as derived in the appendix, would now require that

$$P(t) + \frac{Q(P(t)) - Q_f(t)}{dQ(P(t))/dP(t)} - C_d' - (\delta + r)/a = 0,$$

i.e., marginal revenue is equated to the marginal production costs in each time period. Since the dominant firm owns a nonexhaustible resource stock, its marginal user cost of the resource is zero. In actuality, for a firm such as Inco, marginal user cost is probably so small that it is not taken into account in decision making. The fringe firms represent competition to the dominant firm only in the short run before their resource stock is exhausted. Since their reserves are finite the dominant firm will eventually obtain monopoly status in the industry. Hence, even when the constraints on adjusting capacity are binding for the fringe firms, any period during which the market structure is competitive will be relatively short lived.

8. Conclusions

A general model, which explains the evolution of market structure in a nonrenewable resource industry, has been presented. This particular industry is characterized by the existence of a dominant firm competing with a group of fringe firms. The factors influencing the direction of the change in market structure are the cost levels

and the size of the resource stocks of the two sectors, the market interest rate, the depreciation rate of capital, the speed of adjustment of the capital stock, and the assumptions concerning the elasticity of market demand. The model allows for and predicts that the position of the dominant firm will change within the industry over time. Under the assumption that the fringe sector can instantaneously change the level of its capital stock it is expected that the market share of the dominant firm will be increasing over time. When the fringe sector is constrained in increasing the level of its capital stock it has been shown that the market share of the dominant firm can be decreasing over time.

In both cases, one firm, the dominant firm, is endowed with both the largest resource stock and the greatest level of existing capacity. The firm sets a price higher than the competitive price for the resource which encourages entry and expansion from the smaller firms. When these firms do not face any constraints on adjusting capacity they immediately expand to the most profitable level of production given the set price. The high price set for the resource by the dominant firm induces a shift in production away from the future and towards the earlier time periods by the fringe sector. The dominant firm, on the other hand, must decrease its production so that the price it set can be maintained in the market. The market share of each sector over time will be as depicted in Figure 9. The fringe sector supplies the bulk of the market in the earlier time periods while the dominant firm provides only the residual. As the firms near exhaustion of their reserves they supply a smaller and smaller

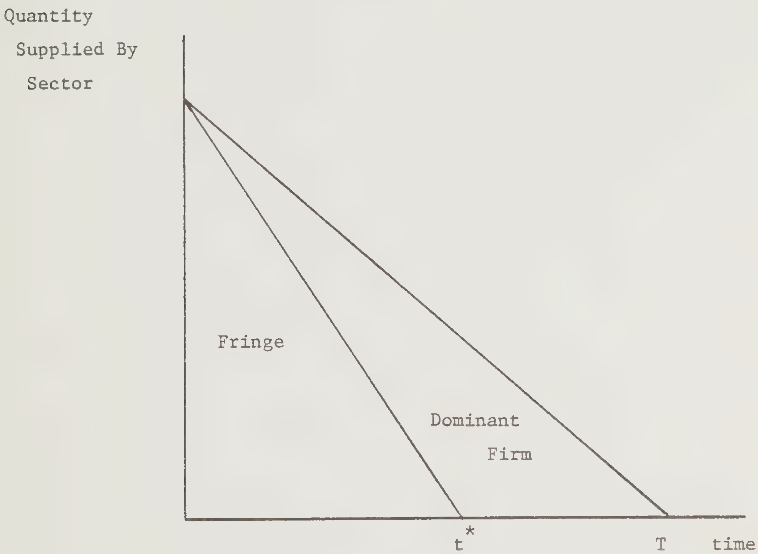

Figure 9.
The Change in Market Structure Over Time: Nonbinding Constraints.

portion of the market. At time t^* the fringe sector exhausts its deposit and the dominant firm becomes the sole supplier of the resource for the industry. It remains as such until it too finally depletes its reserve.

When the fringe sector faces significant constraints on increasing its capital stock, the opposite result is expected. In this case the high price set by the dominant firm encourages entry and expansion, but, due to the constraints on increasing capacity, the competitive fringe supplies only a small portion of the market in the earlier time periods. The dominant firm, on the other hand, provides the bulk of the resource demanded in the market. It is extracting more of its reserve at an earlier date, compared to the previous case. This effect, along with the expansion and entry from the fringe sector, serves to erode the market share of the dominant firm over time, as depicted in Figure 10. If the constraints on the fringe sector are sufficiently binding, the dominant firm will have depleted the major portion of its resource stock and lost so much market share that the industry becomes competitive for the remainder of the time horizon once the constraints have been overcome. The dominant firm is not concerned about its loss in market share since it was able to sell most of its reserve in the earlier time periods.

The amount of concern by the dominant firm over its falling market share is decreased when the demand for the resource is growing over time. The dominant firm may choose to use the proceeds from the sale of the resource to engage in research and development of new products and markets for the resource. The growth in demand may

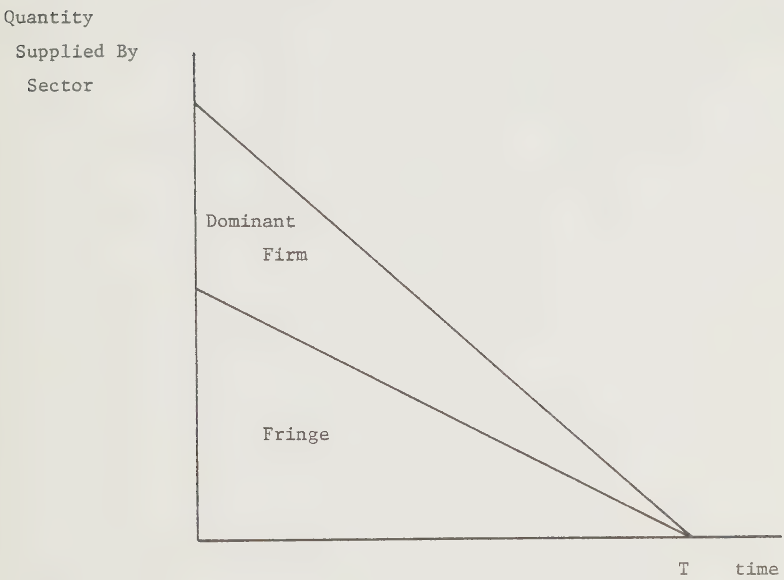

Figure 10.
The Change in Market Structure Over Time:
Sufficiently Binding Constraints.

encourage the dominant firm to increase its rate of production over time even though its share of the market is declining. It may be expected that in an actual mineral resource industry such as the nickel industry the fringe firms, which are also expanding production, will move into the more traditional markets for the resource and not compete in the newer markets established by the dominant firm. As in the previous cases, however, the dominant firm will eventually cut back on the level of its production as the date of the ultimate exhaustion of its reserve draws near.

The inclusion of constraints on increasing capacity has allowed for an extension of the nonrenewable resource literature. Previous analysis has concluded that the dominant firm will eventually obtain a monopoly position within the industry. This result, however, fails to explain the empirical history of the nickel industry, in which the dominant firm, Inco, has lost its market share over time and the industry has become more competitive. The present analysis has developed the conditions under which such a change in market structure is expected. Further, the results of Stephen W. Salant (1976) and Richard J. Gilbert (1978) can be shown to hold as special cases of the more general theory. This analysis implies, then, that the loss in market share experienced by Inco may have been optimal from the firm's long-run point of view.

One final conclusion stemming from the present analysis is concerned with the rate of change of the resource price over time. It has been shown that the market price of the resource will generally not be increasing at a rate equal to the market interest rate.

Instead, in earlier time periods when the marginal user cost of the resource is low relative to the marginal production cost, market price will be increasing at a rate less than the interest rate. When there exist significant constraints on increasing capacity, the change in price may show little relationship to the interest rate and may even be decreasing for a period of time. Market price eventually increases at a rate approximating the interest rate but this will not occur until late in the time horizon, when the marginal user cost of the resource will be large relative to marginal production costs. This result helps to explain the limited empirical justification for the Hotelling rule.

CHAPTER V

EMPIRICAL ANALYSIS OF THE NICKEL INDUSTRY

1. Introduction

Chapter IV presented a theoretical model that describes the actions of a dominant firm in a nonrenewable resource industry under two contrasting assumptions. In one case, the competing fringe operates without any constraint on the speed of adjusting its capital stock; in the alternative case, capital adjustments are limited to some degree. If the constraints on adjusting capital quickly are nonbinding for the fringe firms, it is expected that the dominant firm will eventually obtain monopoly status in the industry. This result stems from the fact that if the dominant firm sets a price higher than the competitive price for the resource, it must conserve its deposit in order to maintain that price. The fringe sector, on the other hand, increases the rate of its production to take advantage of the higher price. At some point the deposits held by the fringe sector will be completely exhausted and the dominant firm enjoys a monopoly position in the industry for the remainder of the time horizon.

If there exist sufficiently binding constraints on the ability of the fringe firms to increase the level of their capital stock, then it is expected that the dominant firm will eventually lose its position in the industry and behave as if it were a member of the competitive sector. In this situation the dominant firm supplies the bulk of the market in the early time periods while the fringe sector

has a limited amount of capital. Over time, the smaller firms are increasing the level of their capital stock and are gaining a larger share of the market at the expense of the dominant firm's share. The dominant firm is not concerned with its loss in market share since it has produced and sold a large portion of its reserve in the earlier time periods while the market price of the resource was above the competitive price.

Previous theories only considered the first possibility, that of an industry structure which becomes more monopolistic over time. The purpose of developing the present model is to account for and theoretically describe the observed trend in market structure as found in the nickel industry. The theoretical analysis has suggested that a pricing policy which encourages entry into the industry can, under certain conditions, be optimal. The purpose of this chapter is to determine if such conditions did exist in the nickel industry and to characterize its history empirically. In Section 2 the different types of data analyzed and their sources are outlined. In Section 3 the trends in production cost and resource prices are analyzed for the nickel industry in order to test the hypothesis of increasing relative scarcity of nickel. In Section 4 it is argued that constraints on increasing capacity quickly were faced by many firms in the nickel industry. In Section 5 the implications of the theoretical model for an industry operating with such constraints are outlined, and in Section 6 the evidence available to support the conclusions of the model are presented.

2. Data Sources

The data examined in this study have been obtained from several sources. Table 1 shows a listing of these data, their unit of measurement, and the data source. A United States (U. S.) price series is utilized since historically nickel prices have been quoted in terms of the U. S. dollar. This series has been adjusted to account for any general inflation over the time period involved. The Canadian series is measured in constant 1982 Canadian dollars and represents the per-unit revenues realized for all nickel products sold by Ontario nickel producers. The cost data are Canadian, reflecting the importance of Canada as a nickel producing country. In addition, the Canadian cost data are the most reliable available. These data are analyzed following the procedures set forth by Harold J. Barnett and Chandler Morse (1963) and Margaret E. Slade (1982). Several interest rate series from the U. S. are utilized in order to determine the relationship between the rate of change of nickel prices and the interest rate.

3. A Test of Scarcity

The theoretical model in Chapter IV was developed under the assumption that the resource being produced is nonrenewable. In its strictest interpretation nonrenewable implies that the resource is also exhaustible; i.e., at some date all possible sources of the resource will be depleted and it will no longer be available. The present analysis, taking into account the likelihood of resource substitution and possible movement down a resource pyramid, takes a more

Table 1.

Data Sources.

Data	Units	Source
Price Series (United States)	$/lb.	Inco, Hist. Stats., and Metal Statistics
Per-Unit Revenue (Canada)	$/kg.	1982 Ontario Mineral Score[1]
Nickel Production (By Country)	ST/Yr.	Minerals Yearbook
Labor Effort (Ontario)	Hr./Yr.	Ontario Metal Mining Statistics[2]
Labor Cost (Ontario)	$/Yr.	Ontario Metal Mining Statistics[2]
Ore Hoisted Metals (Ontario)	ST/Yr.	Ontario Metal Mining Statistics[2]
Nickel Production (Ontario)	MT/Yr.	Towards a Nickel Policy for Ontario[3]
Tonnage of Ore Milled (Ontario)	MT/Yr.	Towards a Nickel Policy for Ontario[3]
GNE Deflator (Canada)	1971=100	Ontario Metal Mining Statistics[2]
Interest Rates (United States)		Economic Report of the President
Price Index (United States)	1967=100	Historical Statistics Statistical Abstracts

[1] Weatherson, G. L. (1983).
[2] Mineral Resources Branch and Centre for Resource Studies (1983).
[3] Mohide, T. P., Warden, C. L., and Mason, J. D. (1977).

realistic view. The model assumes that a certain form of the resource, such as nickel obtained through land based mining compared to sea based mining, is being exhausted as opposed to the resource itself being exhausted. That is, while the nickel obtained from the Sudbury, Canada, or the Kambalda, Australia, areas will eventually be depleted at some date, though maybe not in the near future, nickel as a resource will still be exploited, perhaps through the mining of manganese nodules from the ocean floor. This assumption of increasing relative scarcity of nickel must be tested to determine the relevance of the present model for the nickel industry. Given the present wide disparity between the cost of obtaining nickel ore from these two sources, and given that large scale sea bed mining is not presently pursued, it may be reasonable to expect that nickel has become more scarce over time as the land based reserves are depleted.[1] Following Barnett and Morse (1963), this hypothesis is tested by examining the trend in labor costs and nickel prices over time.

This brings into focus the intertemporal nature of the decision making involved in the production of a nonrenewable resource. The extraction and sale of a unit of the mineral today prevents the extraction and sale of that unit at some date in the future; therefore, as a reserve is exploited the resource remaining in the ground

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[1]The reader should again note that the term scarcity does not imply shortages, but simply that a smaller resource base is available as reserves are exploited. As long as prices are allowed to adjust long term shortages will not occur. See the discussion in the summary section of Chapter II.

will increase in value to the firm. In addition, the cumulative effect of the depletion of a deposit can lead to increasing per-unit costs of production. These increasing costs may be due to either a declining quality of the ore or the simple fact that as a reserve is exploited, the mining activity must be carried out deeper and deeper into the ground. The first question to be addressed then is to determine if increasing costs have been experienced in the nickel industry.

An index of per-unit labor costs for the extraction of mineral ore is constructed for the Province of Ontario, Canada. As figures are not available for nickel mining alone, the metal mining costs considered include copper, nickel, silver, uranium, and other metal mines except for gold and iron mines. The general index obtained represents the total labor costs of mining the above ores. Two separate measures of labor costs are considered. The first series measures the total time requirement of workers engaged in mining activities over the years 1951-1977. The second measures the total wages paid to workers engaged in mining activities, adjusted for any inflation, over the years 1951-1977. Each series is then divided by the total quantity of ore hoisted in a given year to obtain a per-unit cost value. The first series is fitted to both a linear and a quadratic time trend, where the trends are based on the equations

$$H(t)/O(t) = A_o + A_1 t + u(t) \tag{5.1}$$

$$H(t)/O(t) = B_o + B_1 t + B_2 t^2 + v(t). \tag{5.2}$$

H(t) is labor cost measured by the total number of hours spent on

mining activities in year t, O(t) is the total quantity of ore hoisted in year t, t is time measured in years (1951 = 0), and u(t) and v(t) are random error terms.

The purpose of fitting a trend to the data is simply to determine how costs have been changing over time. The linear trend is fitted in order to determine if the data can be described as increasing or decreasing over time. Slade (1982) suggests that the data should also be tested for a quadratic trend. The purpose of doing so is to test for the possibility of a U-shaped time path in cost. This trend may arise when technological innovation occurs in the early part of the time period, but at some point reaches its natural limit, and cost begins to rise due to a lower quality of ore being mined. That is, if the coefficient of time is negative but that of time squared is positive, and both are significant, it could suggest that cost has been decreasing in the early time periods and increasing in the later periods. Or, on the other hand, if the estimated coefficients of time and time squared in the equation are both positive and significant, it would suggest that cost has been increasing at an increasing rate, as opposed to increasing at a constant rate.

The results of estimating equations (5.1) and (5.2) are summarized in Table 2.[2] $\tilde{A}_i$ represents the estimated value of the parameter A_i; $\tilde{B}_i$ signifies the estimated value of B_i. The calculated t sta-

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[2]Since the Durbin-Watson statistics obtained from ordinary least squares regression suggest that the error terms u(t) and v(t) are autocorrelated, the data is transformed following a first order difference procedure. The coefficient of autocorrelation, ρ, is estimated via the procedures set forth by D. Cochrane and G. H. Orcutt (1949) and G. Hildreth and J. Y. Lu (1960).

tistic is shown in parentheses beneath the estimated value of each parameter. The values of R^2, the F-statistic, and the estimated coefficient of autocorrelation, $\tilde{\rho}$, are also shown. The estimated coefficient of time in equation (5.1) is negative and significant. This result tends to suggest that the time requirement of labor per-unit of output has been declining over time. The estimated coefficient of time in equation (5.2) is also negative and significant; that for time squared is positive but insignificant. This result gives additional support to the above conclusion that the time requirement of labor has been decreasing over the time period considered. In both cases the F-statistic obtained indicates that the independent variables, time and time squared, significantly explain the variation in the dependent variable, the per-unit time requirement of labor. The per-unit labor cost measured by the time requirement of labor is shown in Figure 11.

Next, the per-unit real cost of labor over time is analyzed. This series extends from 1951 through 1977. Since the total cost of labor is simply the number of hours worked times the wage rate, multiplying (5.1) and (5.2) through by the real wage rate of labor suggests the estimation of

$$(5.3) \qquad W(t)\cdot H(t)/O(t) = A_o + A_1W(t) + A_2tW(t) + u(t)$$

$$(5.4) \quad W(t)\cdot H(t)/O(t) = B_o + B_1W(t) + B_2tW(t) + B_3t^2W(t) + v(t).$$

W(t) is the average real wage rate obtained by dividing the total wages paid to workers engaged in mining activity by the number of hours worked in each year, H(t) and O(t) are defined as above, t is

Table 2.
Fitted Linear and Quadratic Trends for the Per-Unit Labor Time Cost of Ore Hoisted.

(5.1)	$\tilde{A}_o$ (t)		$\tilde{A}_1$ (t)	R^2	F	$\tilde{\rho}$
	1.4219^a (15.37)		-0.0197^a (-3.49)	0.739	67.97^a	0.511
(5.2)	$\tilde{B}_o$ (t)	$\tilde{B}_1$ (t)	$\tilde{B}_2$ (t)	R^2	F	$\tilde{\rho}$
	1.5896^a (11.48)	-0.0512^b (-2.33)	0.0011 (1.454)	0.760	36.46^a	0.458

Per-Unit Labor Cost Measured in Hours Worked
1951-1977, Number of Observations = 26

[a] Significant at the 01 % level.
[b] Significant at the 05 % level.

time measured in years (1951 = 0), and u(t) and v(t) are random error terms.

The estimated coefficients of equations (5.3) and (5.4) are shown in Table 3. The estimated coefficients of the independent variables in equation (5.3) are not significantly different from zero. While in equation (5.4) the estimated coefficient of wages is insignificant, that of the wage rate times time is negative and significant, and that of the wage rate times time squared is positive

Figure 11.
Per-Unit Time Requirement of Labor: 1951–1977

Table 3.
Fitted Linear and Quadratic Trends for the Real Per-Unit Money Cost of Ore Hoisted.

	$\tilde{A}_o$ (t)	$\tilde{A}_1$ (t)	$\tilde{A}_2$ (t)	R^2	F	$\tilde{\rho}$
(5.3)	1.5586[a] (3.158)	-0.0641 (-0.40)	-0.003 (-1.19)	0.731	31.17[a]	0.541

	$\tilde{B}_o$ (t)	$\tilde{B}_1$ (t)	$\tilde{B}_2$ (t)	$\tilde{B}_3$ (t)	R^2	F	$\tilde{\rho}$
(5.4)	1.5949[a] (3.424)	-0.0115 (-0.07)	-0.0139[b] (-2.47)	0.0004[b] (2.094)	0.769	24.46[a]	0.385

Per-Unit Labor Cost Measured in Real Money Terms
1951-1977, Number of Observations = 26

[a]Significant at the 01 % level.
[b]Significant at the 05 % level.

and significant. This implies that per-unit labor cost was falling in the earlier time periods but rising in the later time periods. This cost is plotted in Figure 12. Together, the information obtained from estimating equations (5.1) - (5.4) suggests that real wages, while increasing, did not keep up with increased productivity in the early years, but seem to have more than compensated the increased productivity in the later years.

Figure 12.
Real Per–Unit Labor Cost: 1951–1977

Before any conclusion can be drawn from this observation, the trend in ore quality must also be examined. This is necessary because the costs studied are those of extracting mineral ore, not of extracting nickel. A change in the quality of the ore will no doubt influence the cost of extracting the metal from the ground. To this end, an index of the nickel content of the total ore milled from nickel and copper mines is fitted to linear and quadratic trends based on the equations

$$Q(t) = A_o + A_1 t + u(t) \tag{5.5}$$

$$Q(t) = B_o + B_1 t + B_2 t^2 + v(t), \tag{5.6}$$

where Q(t) is the ratio of total nickel production to the tonnage of ore milled in nickel and copper mines for the Province of Ontario, Canada at time t, t is time measured in years (1946 = 0), and u(t) and v(t) are random error terms. The results of the regression analysis of equations (5.5) and (5.6) are summarized in Table 4. Since the estimated coefficient of time in equation (5.5) is not significantly different from zero, no inference concerning the trend in ore quality can be made based on the linear trend. However, the estimated coefficients of time and time squared in equation (5.6) are both significantly different from zero. The estimated coefficient of time is negative and that of time squared is positive. This result implies that the quality of the ore was declining in the early part of the relevant time period but has been increasing over the later part. The observed quality of the Ontario nickel ore is shown in Figure 13.

Table 4.
Fitted Linear and Quadratic Trends for the Quality of Ore Milled: 1946-1975.

(5.5)	$\tilde{A}_o$ (t)	$\tilde{A}_1$ (t)		R^2	F	$\tilde{\rho}$
	0.0097^a (10.56)	-0.00002 (-0.48)		0.558	34.13^a	0.665
(5.6)	$\tilde{B}_o$ (t)	$\tilde{B}_1$ (t)	$\tilde{B}_2$ (t)	R^2	F	$\tilde{\rho}$
	0.0118^a (12.67)	$-.00035^b$ (-2.59)	0.00001^b (2.309)	0.616	20.81^a	0.483

Number of Observations = 29

[a]Significant at the 01 % level.
[b]Significant at the 05 % level.

To determine any change in the labor cost of extracting nickel over time from the available cost and quality trend information, the results from estimating equation (5.4), that of per-unit costs measured in real terms, can be compared to the results obtained from estimating equation (5.6). In both cases the estimated coefficient of time is negative and significant, that of time squared is positive and significant. This combined information tends to suggest that the per-unit labor costs of extracting the resource from the ground and

Figure 13.
The Quality of Nickel Ore: 1946–1975.

the quality of the ore have moved in the same direction over time. Since both tended to fall in the early time periods and have possibly risen in the later time periods, no conclusion concerning the relative scarcity of nickel can be drawn from this information alone.

The next step then is to determine if the value of nickel in real terms has been changing over time. If the value of nickel has been increasing in real terms over time, it can be concluded that nickel as a resource is characterized by increasing scarcity. This can be determined by testing for any trend in real nickel prices over time. Two price series are considered. The first series measures the per kilogram value of nickel measured in 1982 Canadian dollars for Ontario nickel producers from 1895 to 1982. The series is obtained by dividing the total value of primary nickel product sales by the total volume of nickel produced in each year. The second series is constructed from several sources[3] and reflects the world market price for an unchanging commodity. The Canadian series, derived from revenues for primary nickel products of ever-increasing value added, reflects the value of a constantly improving product. Each price series is then fitted to a linear and quadratic trend based on the equations:

$$(5.7) \qquad P_i(t) = A_{oi} + A_{1i}t + u_i(t) \qquad i = 1,2$$

$$(5.8) \qquad P_i(t) = B_{oi} + B_{1i}t + B_{2i}t^2 + v_i(t) \qquad i = 1,2$$

[3]Prices from 1840-1912 furnished by Inco, from 1913-1945 by *Historical Statistics*, and from 1946-1982 by *Metallgesellschaft*.

Table 5.
Fitted Linear Trend for Real Nickel Prices.

(5.7)	$\tilde{A}_o$ (t)	$\tilde{A}_1$ (t)	R^2	F	$\tilde{\rho}$
1	1.668[a] (2.895)	0.0710[a] (6.646)	0.936	1246.7[a]	0.79
2	4.9633[a] (3.301)	-0.0369[a] (-2.3)	0.937	2063.3[a]	0.927

1 - Canadian Revenue Series in 1982 Dollars
1895-1982, Number of Observations = 87

2 - U. S. Real Price Series in 1967 Dollars
1840-1982, Number of Observations = 142

[a]Significant at the 01 % level.

$P_i(t)$ represents the two series, t is time measured in years (1895=0, i=1; 1840=0, i=2), and $u_i(t)$ and $v_i(t)$ are random error terms. The subscript i=1 signifies the Canadian real per-unit revenue series, and i=2 the U. S. real price series. The results of estimating equation (5.7) are summarized in Table 5, and those for equation (5.8) are found in Table 6.

The estimated coefficient of time in equation (5.7) for the Canadian revenue series is positive while that for the U. S. price

Table 6.
Fitted Quadratic Trend for Real Nickel Prices.

(5.8)	$\tilde{B}_o$ (t)	$\tilde{B}_1$ (t)	$\tilde{B}_2$ (t)	R^2	F	$\tilde{\rho}$
1	1.9875[b] (2.141)	0.0522[c] (1.174)	0.0002 (0.441)	0.936	617.30[a]	0.779
2	8.4702[a] (8.371)	-0.1608[a] (-5.33)	0.0008[a] (4.129)	0.940	1094.1[a]	0.836

1 - Canadian Revenue Series in 1982 Dollars
1895-1982, Number of Observations = 87

2 - U. S. Real Price Series in 1967 Dollars
1840-1982, Number of Observations = 142

[a]Significant at the 01 % level.
[b]Significant at the 05 % level.
[c]Significant at the 10 % level.

series is negative; both coefficients are significant. The difference in the signs of the coefficients can be easily explained. The Canadian series represents the per-unit revenues from a constantly changing product, the upward trend being attributed to the increasing quality of primary nickel products. On the other hand, the U. S. series represents the market price of a constant quality product; the downward trend is, therefore, quite likely the result of

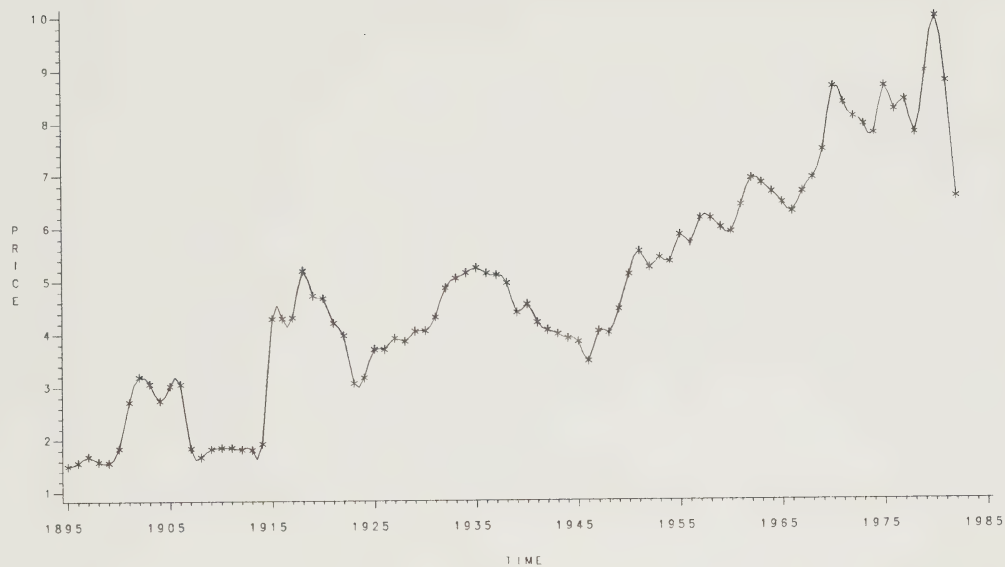

Figure 14.
Canadian Real Nickel Revenues. 1895–1982

the increased availability of nickel since it first came into use.

The results of estimating equation (5.8) for the Canadian revenue series again suggest a strictly upward trend; the estimated coefficient of time is positive and significant; that of time squared is also positive but is not significant. Estimation of equation (5.8) for the U. S. price series implies that nickel prices have not been strictly declining over time. While the estimated coefficient of time is negative, the coefficient of time squared is positive; both are significant. This implies somewhat of a U-shape trend for nickel prices, first declining then increasing.[4] As suggested previously, the early decline in nickel prices can be attributed to the increased availability of nickel as the Canadian reserves were developed in the late 1800's and early 1900's. The upward trend in nickel prices over the later half of the time perod may be due to such factors as the many new uses and markets developed for nickel by Inco throughout the period and the growth in the major economies following the second world war.

The Canadian revenue series is shown in Figure 14 and the U. S. price series in Figure 15. It should be noted that while the analysis shows that nickel prices have been increasing over time, there is no reason to suggest that the upward trend will or will not continue.

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[4]In analyzing U. S. nickel prices from 1910 through 1980, Margaret E. Slade (1982) finds the estimated coefficient of time for equation (5.7) to be both positive and significant. For equation (5.8), the estimated coefficient of time is negative and that of time squared is positive, this suggests a U - shape to the U. S. series, with prices falling in the earlier years and rising in the later years.

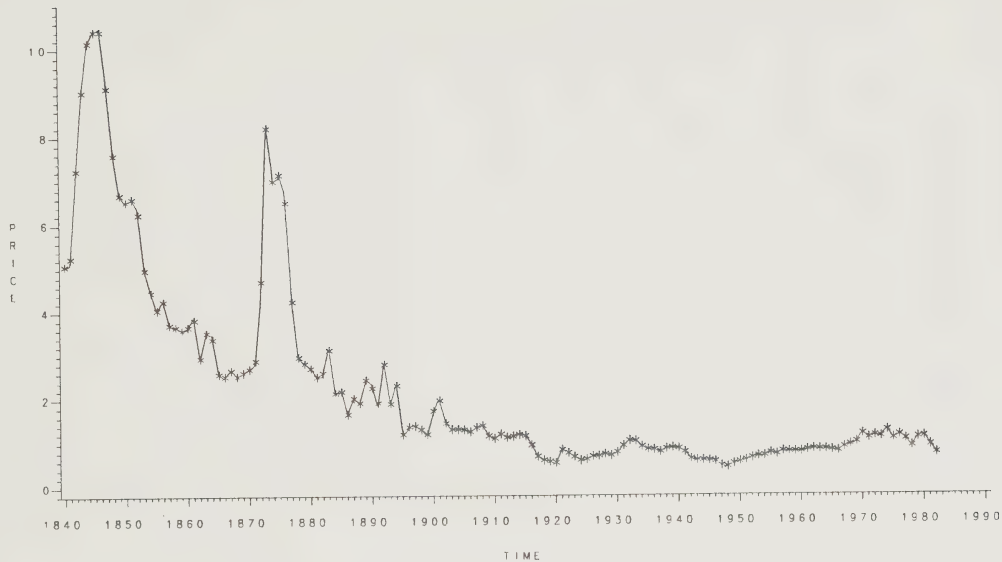

Figure 15.
United States Real Nickel Prices: 1840–1982.

This will depend on such factors as the substitutablity of nickel, technological innovation, and future supply and demand conditions in the industry.

4. Constraints in the Nickel Industry

In the model presented, market structure in a nonrenewable resource industry can change in two opposite directions depending on whether or not there exist constraints on increasing the level of capital quickly. It will be argued that such constraints were in fact faced by firms in the nickel industry. The various forms in which the constraints may have actually existed will be discussed below. The constraints on increasing capacity quickly in the nickel industry can be grouped into three separate catagories; those associated with obtaining a viable deposit of nickel, those related with developing the deposit, and those having to do with producing and selling the finished nickel.

It is quite obvious that the first hurdle any firm in the nickel industry must overcome is that of locating a suitable reserve of nickel ore. It appears that some of the early nickel deposits were found by chance, while most of the later ones were the result of planned exploration. Among those reserves discovered without exploration for nickel *per se*, the majority were located as the result of developing deposits for other metals. The earliest nickel deposits mined in Europe were found in conjunction with silver and copper mines. Similarly, the world's largest deposit of nickel, found in Canada, was first mined for the copper contained in the ore. Even in

Australia, where a large amount of exploration did take place, the first hints that there was nickel to be found came during the early gold rush days.

To say that all of the deposits were found in this manner, though, would not be true. Soon after the French gained control of the island of New Caledonia, the government commissioned a detailed geological study of the area. This study noted the abundance of nickel ore deposits on the island and efforts to develop them were soon underway. This type of scenario also describes the discovery of nickel deposits in Cuba, the Philippines, and South America.

An important point to note is that while many different countries were known to have some nickel reserves in the early part of the twentieth century, in most cases the extent and quality of the deposits were not known for many years or even decades later. As is common in most mineral resource industries, all of the world's nickel deposits were not discovered and developed at the same time but rather were located at different points in time under various circumstances, and the decision to exploit them did not immediately follow their discovery. The various nickel deposits of the world were brought into production over a period of about one hundred years. The search for an economically viable deposit appears to have kept some countries from producing nickel in the early years.

The second problem faced by nickel producers centered around extracting the nickel ore from the ground. Given that the world's nickel deposits have been found in virtually undeveloped, uninhabited areas, a certain infrastructure had to be built up before any large

amount of production could begin. First, roads or railroads had to be constructed in order to bring materials, workers, and supplies to the site of the deposit. Secondly, a small town composed of homes, a hospital, school, churches, and stores had to be built for the workers and their families. In addition, the mining facility itself had to be constructed. Finally, an energy source had to be found. This is accomplished by either obtaining a steady supply of fuel oil or developing some type of electric generating station.

The last constraint facing potential nickel producers centers around the delivery of the finished product to the market. This type of constraint seems to have taken one of two forms in the nickel industry. The first is in developing an adequate refining process for the particular type of ore that any one firm might have. This appears to have been a major problem for the early nickel producers and a lesser one to the firms which entered the industry in later times. The reason is that while the first producers of nickel had to develop a completely new refining process for the ore, the later firms were able to adapt one of these processes to their own deposits.

The other, less common, constraint deals with the problems of bringing the finished nickel to the market. One country particularly affected in this manner has been New Caledonia. In the first half of the twentieth century, especially during the war years, the producers in this country faced great difficulty in obtaining an adequate supply of ships to transport the nickel. Later, Brazil appears to have faced similar trouble in obtaining land transportation through its

jungle areas.

Table 7.
Constraints Faced By Developers of Several Important Nickel Deposits.

Deposit Location (Principal Developer)	Time	Development Problems
Oriente Province, Cuba (Nicaro Nickel Co.)	12	Need for a Refining Process Construction of Plant, Facilities Mechanical Difficulties Production Halted 4 Years Revolution in Cuba
Kambalda, Australia (Western Mining Co.)	12	Construction of Plant, Facilities Transportation Network Slow Expansion of Capacity Financing
Nonoc Island, Philippines (Marinduque Mining Co.)	10	Government Approval Construction of Plant, Facilities Financing Inadequate Energy Source Equipment Problems Plant Redesigns Training of Personnell

This information has been obtained from various issues of the Minerals Yearbook.

While an account of these difficulties faced by the developers of certain nickel deposits has been presented in Chapter III, a summary of the constraints overcome in developing several of the more important nickel deposits is given in Table 7. The location of the

deposits and the principal developer is listed in column one. Column two shows the approximate amount of time that was required to bring the deposit up to full scale production levels. It is measured from the time a decision was made to develop the deposit up to the point where there were no more significant increases in output from the reserve. It should be noted that an accounting of the time required for exploration is not made; this will in general add between five and ten years to the required development time. A summary of some of the difficulties overcome in developing the reserve is given in column three. It appears from this information that firms in the nickel industry were constrained in increasing capacity quickly by the various problems discussed. This implies that an assumption of instantaneous or even reasonably quick capital adjustments, at least for the nickel industry, is not very realistic.

5. Implications of the Model

The theoretical model presented in Chapter IV has several implications for a nonrenewable resource industry in which the smaller firms face sufficient constraints on increasing the level of capital stocks quickly. The first of these is rather explicit and concerns the trend over time of market structure. In particular, the dominant firm in the industry is expected to lose market share over time as the smaller firms invest in and expand the level of their capital stock. This entry and expansion is encouraged by the dominant firm setting a price higher than the competitive price, yet it is realized that due to the constraints faced by the fringe firms it may be quite

a long period of time before the dominant firm loses its position. It has also been shown that the effect of growth in demand serves to increase the period of time over which one firm is dominant. It is expected then, that over time the market share of the dominant firm will be decreasing if the fringe firms originally face constraints on increasing capacity. It may also be the case that the number of nickel producers will be increasing over this time period.

From this result, several other implications for the industry can be inferred. During the period of time in which the dominant firm has a large market share, it should also exert considerable influence over the market price of the resource. It can also be expected that as the firm's market share diminishes so will its ability to manipulate the market price. There would then be a period of time in which price is set by the dominant firm and adhered to by all other firms, followed by a period of time in which the dominant firm's ability to determine prices is challanged by other firms, and finally a period at which some agreeable method or institution is employed to indicate the price of the resource in the market. This price will be determined solely by the existing supply and demand conditions in the industry.

It can also be inferred that there would be fewer changes in the price of the resource during the earlier periods in which one firm held a dominant position than there would be in the later periods. This is suggested by the conclusion reached in the theoretical chapter that the rate of change in resource prices will be slower in the constrained case than in the unconstrained. A high price would be

set by the dominant firm given that only a small amount of production would be forthcoming from the fringe sector. While these firms were expanding their production levels, the dominant firm would have to decrease its production to keep the resource price from falling when demand is constant. If the dominant firm maintained its production level, the resource price would have to fall as the smaller firms expand. If demand is growing over time, the dominant firm may be able to maintain or even expand its level of production with no effect on price from the increasing fringe production. Once the constaints were overcome and all firms were producing at full scale production levels defined by profit maximization the price of the resource would be expected to be increasing as the reserves are depleted.

The model also predicts that while the constraints on increasing capacity are binding for the fringe firms there should be little or no relationship between net price and the market rate of interest. This is a novel result in the sense that previous theoretical models predict that there would be a direct relationship. Most empirical studies, however, fail to support this claim. The present model argues that the expected exponential growth in net price will not surface until after all constraints on increasing the capital stock have been overcome. One of the purposes of the present study is to investigate the observed history of the nickel industry. It has been shown that if the constraints on increasing capacity are sufficiently binding for fringe firms in a nonrenewable resource industry, the industry would be characterized by a decreasing market share for the

dominant firm, little change and virtual control of the resource price by the dominant firm while it has a large share of the market, and increasing prices and no control of price by any firm as the industry becomes competitive.

6. Evidence From the Nickel Industry

An investigation of the nickel industry brings to light several important characteristics which will be employed to verify that there did exist constraints on increasing capacity in the industry. The first of these is the slow yet steady decline in market share obviously experienced by Canada and Inco throughout the twentieth century as shown in Table 8. In 1929 Inco held over ninety percent of the world market in nickel production. By 1981 Canada's market share had dropped to under 23 percent of total world production and Inco, which remained the world's largest nickel producing firm, had a world market share of less than 16 percent. It should be noted that there was never any sharp drop in market share but a steady decline, which took over fifty years to occur. During this same period of time the share of nickel produced by the U.S.S.R. has steadily risen, and is now nearly equal to that of Canada. New Caledonia's share, on the other hand, has fluctuated from a low of 3 percent to a high of almost 17 percent. Australia, a relative newcomer in the industry, had a share of almost 10 percent in 1980.

Some additional information about the industry can be obtained by analyzing the trend in Canada's share of the market over time. A linear and quadratic trend are fitted to the market share data for

Table 8.
The Percentage Share of Nickel Produced By Country: 1930-1980.

Year	World*	Australia	Canada	New Caledonia	U.S.S.R.
1930	059734	00.2	86.7	09.0	0.00
1935	085318	0.00	81.2	10.6	02.4
1940	154323	0.00	79.6	07.5	06.2
1945	159834	0.00	76.7	03.0	09.2
1950	162000	0.00	76.3	02.9	19.8
1955	264000	0.00	66.3	06.8	18.2
1960	353000	0.00	60.8	12.3	16.4
1965	468346	0.00	57.1	11.3	19.2
1970	692710	04.7	44.2	16.8	17.3
1975	890532	09.4	30.0	16.5	18.9
1980	836312	09.8	24.4	11.4	20.3

*Total World Nickel Production in Short Tons

Canada based on the equations

(5.9) $$S(t) = A_o + A_1 t + u(t)$$

(5.10) $$S(t) = B_0 + B_1 t + B_2 t^2 + v(t).$$

S(t) signifies the percentage share of the world's nickel produced by Canada at time t, t is time measured in years (1930 = 0), and u(t) and v(t) are random error terms. The estimated trend coefficients for equations (5.9) and (5.10) are shown in Table 9. The estimated coefficient of time for equation (5.9) is negative and significant. This result simply restates what is already known, Canada's percentage share of world production has been decreasing over time. For equation (5.10), the estimated coefficient of time is not significantly different from zero and that of time squared is negative and highly significant. This result implies that Canada's share of world production was declining at a faster rate in the later time periods than in the earlier time periods. This suggests that the other countries were unable to expand production quickly when they first entered the industry, but once capital stocks were built up the expansion of production occurred at a faster rate.[5] Inco's percentage share of world production over time is shown in Figure 16.

An interesting point to consider is the contrasting way in which Inco conducted its business through the 1960's with the manner in which it has since that time. Originally, Inco would announce what was called the producer price for nickel on a regular basis. This price would then be adopted by all other producers of nickel without question. Inco's leadership in setting prices was not challenged to

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[5] An alternative conclusion might be that Canada was not able to increase production quickly enough to meet the growing demand for nickel. Conversations with industry officials and taking note of Canada's history of its ability to expand production imply that this conclusion may not be relevant.

Table 9.
Fitted Linear and Quadratic Trends for Canada's Share of World Production: 1930-1981.

				R^2	F	$\tilde{\rho}$
(5.9)	$\tilde{A}_o$ (t)	$\tilde{A}_1$ (t)				
	0.9567[a] (16.14)	-0.0135[a] (-7.46)		0.95	922.86[a]	0.763
(5.10)	$\tilde{B}_o$ (t)	$\tilde{B}_1$ (t)	$\tilde{B}_2$ (t)	R^2	F	$\tilde{\rho}$
	0.7931[a] (32.70)	0.0027 (1.256)	-0.0003[a] (-7.5)	0.964	637.24[a]	0.276

Number of Observations = 51

[a]Significant at the 01 % level.

any great extent until the early seventies. Prior to that time Inco supplied nickel on a non contractual basis. It allowed the other firms to supply as much as they could at the price set by Inco and then supplied any excess demand remaining in the market. As Canada's market share decreased, however, Inco found itself less and less able to influence the market.

The 1970's can be characterized as a period of transition for the nickel industry and for Inco. While Canada held over 44 percent of the world market in 1970, by 1979 this share had dropped to less

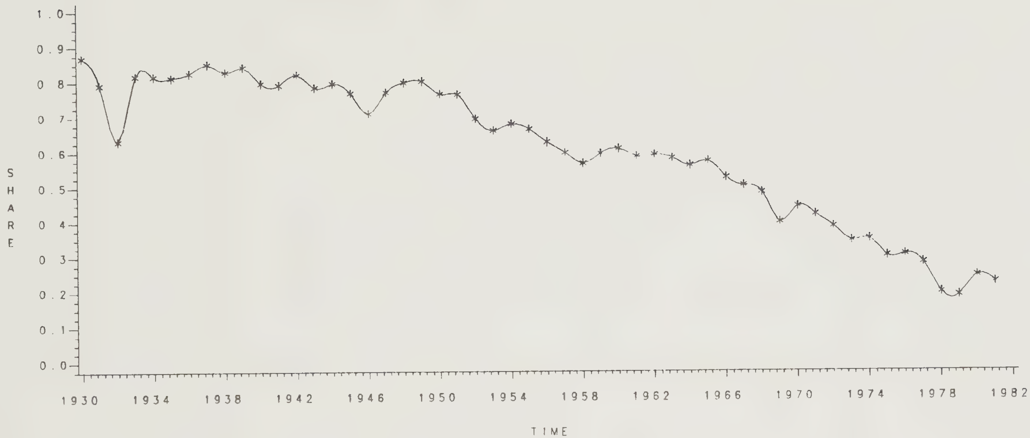

Figure 16.
The Share of Nickel Produced By Canada: 1930–1981.

than 19 percent. Inco was challanged in its price leadership role to such an extent that the producer price was dropped altogether in 1977. In 1979 nickel was first traded on the London Metal Exchange (LME), though it accounted for only one percent of all nickel transactions. As time passed the importance of the LME price for nickel increased, in the sense that it has replaced Inco's producer price as the industry's indicator of price. While the price charged by Inco is generally higher than that found on the LME, it is not much higher and the difference can be attributed to the fact that terms for nickel on the LME are cash and carry.

A final area of investigation is in determining the relationship, if any, between the rate of change of price and the market rate of interest. The theoretical model developed in Chapter IV argues that the rate of change of the resource price will be equal to the interest rate times the ratio of the marginal user cost of the resource to the marginal user cost of the resource plus the marginal production costs; i.e.,

$$(5.11) \qquad \frac{\dot{P}(t)}{P(t)} = r\{ \frac{\lambda_f e^{rt}}{\lambda_f e^{rt} + C_f' + \mu_f} \}$$

where C_f' represents marginal costs and μ_f the shadow price of capital, both for the fringe sector. To adequately estimate equation (5.11), accurate measures of the marginal user cost of the resource, marginal production costs, and the shadow price of capital are needed. Further, equation (5.11) assumes that the production costs be constant over time, which may or may not be a reasonable assump-

tion. Unfortunately, limitations on the availability of reliable cost data prevent the undertaking of a more rigorous analysis. Given these constraints, a simple relationship between the rate of change of nickel prices and the interest rate is tested. The equation estimated to test this relationship is

$$(5.12) \qquad \frac{P(t + 1) - P(t)}{P(t)} = \Theta_o + \Theta_1 r_j(t) + u(t) \quad j = 1,2,3$$

where P(t) is the price of nickel in the United States in year t, $r_j(t)$ j = 1,2,3 represents different U. S. interest rate series, and u(t) is a random error term. The results of estimating equation (5.12) are summarized in Table 10. In all cases, the estimated coefficient of the interest rate is not significantly different from zero. It can be concluded then that no strong relationship has existed between the rate of change of nickel prices and the various interest rates examined.

A closer examination of actual prices in the nickel industry shows that prior to 1970 nickel prices were relatively stable. A listing of the number of price changes per year is given in Table 11. The number of nickel producing countries in each year is also shown. It appears that in the early years Inco followd a strategy of setting a price for nickel which encouraged entry and then adjusted its output to maintain that price. In the 1950's though the accumulated entry began to have its effect on the market and the decline in Canadian market share became a reality. As the number of countries producing nickel and the amount they produced steadily grew, price began

Table 10.
The Relationship Between The Rate of Change of Price and the Interest Rate: United States.

(5.12)	$\tilde{\Theta}_o$ (t)	$\tilde{\Theta}_1$ (t)	R^2	F
1	0.0839 (2.068)	-0.4397 (-0.68)	0.014	0.464
2	0.0891 (2.138)	-0.4625 (-0.7)	0.018	0.633
3	0.0978 (2.342)	-0.9009 (-1.03)	0.030	1.050

1 - Moody AAA Bond Rating

2 - Moody BBB Bond Rating

3 - High Grade Municipal Bond Rating

1946-1982, Number of Observations = 36

to reflect less the actions of Inco and more the actual supply and demand conditions existing in the industry. It is reasonable to claim that most of the constraints on increasing capacity had been overcome by the early 1980's. It may be expected then that nickel prices will remain at the competitive level for some years to come; that is, it is not expected that any one firm will have anywhere near the amount of market power Inco once did. In this regard, the price

Table 11.
The Number of Price Changes Per Year in the Nickel Industry: 1930-1981.

Year	Share	#Δ	#P	Year	Share	#Δ	#P
1930	86.7	00	06	1956	62.6	01	14
1931	79.2	00	06	1957	59.7	00	15
1932	63.1	00	07	1958	56.5	00	15
1933	81.6	00	08	1959	59.4	00	16
1934	81.5	00	08	1960	60.8	00	17
1935	81.2	00	12	1961	58.5	01	16
1936	82.4	00	12	1962	58.9	01	14
1937	84.9	00	13	1963	58.0	00	14
1938	82.7	00	16	1964	55.9	00	14
1939	84.1	00	17	1965	57.1	00	13
1940	79.6	00	15	1966	52.5	01	13
1941	79.0	00	16	1967	50.2	01	17
1942	81.9	00	16	1968	48.2	00	17
1943	78.2	00	15	1969	39.8	02	17
1944	79.3	00	15	1970	44.2	01	17
1945	76.7	00	14	1971	41.9	00	19
1946	70.9	00	08	1972	38.4	03	20
1947	76.9	00	07	1973	34.4	01	22
1948	79.7	03	05	1974	34.9	10	22
1949	80.0	00	06	1975	30.0	08	22
1950	76.3	02	05	1976	30.4	09	23
1951	76.2	01	07	1977	28.1	09	24
1952	69.2	00	10	1978	19.5	07	24
1953	65.9	01	10	1979	18.6	10	24
1954	67.8	01	12	1980	24.4	12	23
1955	66.3	00	13	1981	22.5	12	23

Share = Canada's Share of World Production for the Year

#Δ = The Number of Months Price Changed for the Year

#P = The Number of Nickel Producing Countries for the Year

of nickel as quoted on the London Metal Exchange will remain an important indicator of nickel prices from now on.

7. Conclusions

From the evidence presented it can be concluded that in its early history Inco has behaved in a manner expected of a dominant firm. It should be noted that in employing the term "dominant firm" in describing Inco no connotation, good or bad, should be carried with it. For whatever reasons, ability or luck, Inco achieved a virtual monopoly position early in the history of the nickel industry. Inco, however, operated in a manner not expected of most monopolists. It set the market price for nickel and also adjusted its output level in order to maintain that price. However, as opposed to limit pricing and trying to protect its near monopoly position, Inco accommodated other firms that entered the industry. Further, the price set by Inco was high enough to encourage entry by other firms into the industry. Eventually, this led to the loss of Inco's dominant position and a very competitive market structure for the industry.

Inco, faced with continued entry and expansion by other firms, was still able to maintain its dominant position in the industry for quite a long period of time. Inco's ability to do so revolves around the fact that Inco's competitors were constrained in the amount of nickel that could be supplied to the market in the earlier time periods. Due to the many obstacles that are faced, a long period of time is required to develop a nickel deposit, aside from the time needed to locate a reserve, so that entry into the industry becomes a very

drawn out process. This is in direct opposition to the typical assumption in exhaustible resource models that firms can instantaneously adjust the level of their capital stock. That these constraints truely existed and were sufficiently binding to the fringe firms is evidenced by the lack of relationship between the rate of change of price and the market interest rate.

In general, exhaustible resource models developed from the Hotelling framework predict a direct relationship between the two. It is argued that if net price were increasing at a rate slower than the interest rate then firms could improve their situation by completely exhausting the deposit and investing the return from doing so at the market rate of interest. One factor that would prevent firms from doing so could be the constraints of the type discussed on increasing capacity quickly. A dominant firm, such as Inco, can then set a very high price for the resource and supply a large portion of the market in the early time periods. By cutting back on its production as other firms increase output the high price can be maintained for a long period of time.

A second way for the dominant firm to maintain its market share and the price it sets for the resource is through engaging in research and development for new products which use the resource. By continually finding new uses for the resource the dominant firm can encourage a growth in demand sufficient to take up the additional output available as firms enter the industry and expand production. In this way the dominant firm develops new markets for its output as other firms take over existing markets.

It appears that Inco employed a combination of these two methods in maintaining its dominant position for such a long period of time. While the high price for nickel set by Inco certainly encouraged entry in to the industry, it also enabled Inco to engage in the research and development necessary to support a sustained growth in the demand for nickel. Indeed, the 1950's and the 1960's can be described as a period of time in which the supply of nickel lagged consistently behind the demand. As long as this was the case, Inco was able to maintain its dominant position in the industry. Although production from the fringe sector had been steadily increasing over this time, it was not until the 1970's that Inco really began to lose its control over the market. Had the other firms been able to enter the industry and expand capacity at a faster rate, Inco would have lost its dominant position at a much earlier date.

CHAPTER VI

CONCLUSION

This study has developed a general model of an exhaustible resource industry characterized by a dominant firm competing with a group of smaller firms. The smaller firms, defined as the competitive fringe, have been modeled as taking price as given, while the dominant firm determines the market price of the resource and then adjusts the level of its production to maintain the set price. The analysis has assumed certainty in the cost of production, the size of the resource stock, and the level of market demand in both present and future time periods. As an important distinction between the present analysis and previous theoretical studies in the area, constraints on the ability of firms to increase the level of their capital stock quickly have been incorporated into the model.

Utilizing this model, the study has shown that when capacity adjustment constraints exist and are sufficiently binding, the market structure of the industry is expected to evolve over time from monopolistic into a dominant firm competing with a group of fringe firms and eventually towards competitive. Further, the rate of change of the resource price is not generally expected to be equal to the market rate of interest, and the rate of change of the resource price less all marginal costs of production is expected to be less than the interest rate. These results are important for two reasons. First, empirical analysis of nonrenewable resource prices alone typically finds that there is little or no relationship between their rate of

change and the interest rate. The present analysis suggests that this is a likely outcome, given that the effect of marginal production costs have been ignored. Secondly, previous theoretical models conclude that an exhaustible resource industry controlled by a cartel or a dominant firm will eventually become monopolistic. This theory, however, fails to explain the observed trend in market structure of the aluminum, copper, diamond, and nickel industries.

The conclusion that the market structure will become monopolistic has been shown to hold as a special case of the model developed when the constraint on increasing capital stocks is not binding. In this instance, the dominant firm, in order to maintain the resource price above the competitive price, must cut back on the level of its production, in effect conserving its resource for a later date. The smaller firms in the industry respond to the increase in price by increasing the rate of their production of the resource. This implies that the fringe sector will exhaust its resource stock at an earlier date, leaving the dominant firm with a monopoly position in the industry. This result must be viewed with caution, however, since it is obtained under the restrictive assumption that firms are able to instantaneously adjust the level of their capital stock.

In the more general case, where the fringe firms are constrained in their ability to increase capital stocks quickly, the opposite trend in market structure may arise. That is, when the constraints are sufficiently binding to the fringe sector, the dominant firm sets a price for the resource above the competitive price that will still encourage an increase in production from the smaller firms, but it

will be a long time before these firms are actually able to expand production. The dominant firm then provides a large share of the market with the resource during the earlier period while the fringe sector is forced to conserve on its resource stock. The fringe sector, expanding its capacity as quickly as possible, gains a larger and larger share of the market over time at the expense of the dominant firm. By the time the adjustment constraints have been overcome by the fringe sector, the dominant firm will have lost its dominant position and will begin to operate as if it were a member of the competitive fringe.

It has been shown then, that, under certain plausible assumptions, the market structure in an exhaustible resource industry is expected to change over time from monopolistic towards competitive. It also appears that this may have been the more relevant case, as evidenced by the empirical history of several nonrenewable resource industries, and in particular the nickel industry.

The world nickel industry was at one time completely dominated by a single firm, the International Nickel Company (Inco) of Canada. Inco held a virtual monopoly position in the industry for a short period of time, which was followed by a very lengthy period during which Inco operated as a dominant firm, setting the market price of nickel and adjusting its output in order to maintain that price. More recently, though, the nickel industry can be described as basically competitive, with Inco producing a relatively small share of the world's nickel and having no major influence on nickel prices, at least not to the extent it once did. It is interesting to determine

if a pricing policy as practiced by Inco which has encouraged substantial entry into the industry and its resulting impact on market share could be optimal from the firm's point of view.

The model that has been developed implies that under certain conditions such a pricing policy can indeed be optimal from the firm's long-run perspective. Data from the nickel industry have been examined to determine if such conditions actually existed in the industry and to help characterize its history. The actual histories of the development of several major nickel deposits were then investigated to isolate any possible problems which may have prevented nickel producers from rapidly developing a nickel reserve. This search has found several factors, some concerned with the problems of building the infrastructure necessary to mine the ore and others with transportation and refining problems, which have led to a development period of from 5 to 15 years to bring a nickel reserve up to full scale production levels. Finally, analysis of Canada's share of world nickel production suggests an accelerated decline in its share over the later part of the time period considered. The evidence implies then that Inco has followed an optimal policy in which it set a high price for nickel in the early years. This allowed Inco to earn a high rate of return during this time period at the cost of future market share. It should be noted, though, that Inco reinvested a great deal of its return on the research and development of new products for nickel. The result of the effort contributed to a period of sustained growth in demand for the nickel industry. This action allowed Inco to maintain its dominant position in the industry

for a much longer time period than if demand in the industry had not been increasing.

APPENDIX A

MATHEMATICAL APPENDIX TO CHAPTER IV

1. The Analytical Framework

The fringe sector, denoted by the subscript f, seeks to maximize the present value of its discounted cash flow

$$\text{(A.1)} \qquad \Pi_f = \int_o^T \{P(t)Q_f(t) - C_f(Q_f(t)) - \delta K_f(t) - \dot{K}_f(t)\} e^{-rt} dt$$

by choosing the rate of output, $Q_f(t)$, and the rate of change of the capital stock, $\dot{K}_f(t)$, in each time period. $C_f(Q_f(t))$ signifies the fringe sector's variable cost function, δ the depreciation rate of capital, and r the market rate of interest. The price of capital is, without loss of generality, assumed to be one. It can be shown that

$$\text{(A.2)} \qquad \int_o^T \dot{K}_f(t) e^{-rt} dt = \int_o^T rK_f(t) e^{-rt} dt - K_f(0)$$

where it is assumed that $K_f(T) = 0$. Equation (A.2) shows that the discounted cost of any adjustments in capacity is equal to the discounted opportunity cost of the capital held over the time horizon less any initial endowment of capital the fringe sector may start out with. Since at time T it is optimal that each firm has exhausted its reserve, in general, the fringe sector does not want any unused capital on hand.

Substituting the right hand side of (A.2) into (A.1) yields the objective of the fringe sector which is, as stated above, to maximize over time the present value of its discounted cash flow

$$\text{(A.3)} \quad \int_o^T \{P(t)Q_f(t) - C_f(Q_f(t)) - [\delta + r]K_f(t)\}e^{-rt}dt + K_f(0)$$

by choosing the optimal level of output and capacity. The solution of (A.3) requires the optimization of the integrand in each time period subject to the constraints

$$\text{(A.4)} \quad K_f(0) = \underline{K}_f \geq 0, \; K_f(T) = 0$$

$$\text{(A.5)} \quad Q_f(t) \leq aK_f(t), \; a > 0$$

$$\text{(A.6)} \quad \int_o^T Q_f(t)dt \leq S_f(0),$$

where $S_f(0)$ denotes the size of the fringe sector's original resource deposit. Formally, the fringe sector seeks to maximize the Lagrangian $\ell_f(Q_f(t),K_f(t),\mu_f,\lambda_f;P(t),\delta,\phi_f,\psi_f,r)$ over all time periods defined by

$$\begin{aligned}\text{(A.7)} \quad & \int_o^T \{P(t)Q_f(t) - C_f(Q_f(t)) - [\delta + r]K_f(t)\}e^{-rt}dt + K_f(0) \\ & + \mu_f(t)[aK_f(t) - Q_f(t)] \\ & + \lambda_f[S_f(0) - \int_o^T Q_f(t)dt]\end{aligned}$$

where $\mu_f(t)$ and λ_f are the Lagrangian multipliers.

The first order conditions which maximize (A.7) in each time period for the fringe sector are

$$\text{(A.8)} \quad [P(t) - C_f'(Q_f(t))]e^{-rt} - \mu_f - \lambda_f = 0$$

$$\text{(A.9)} \quad -(\delta + r)e^{-rt} + \mu_f(t)a = 0$$

$$\text{(A.10)} \quad aK_f(t) - Q_f(t) = 0$$

$$\text{(A.11)} \quad S_f(0) - \int_o^T Q_f(t)dt = 0$$

$$\text{(A.12)} \quad \mu_f(t), \; \lambda_f > 0.$$ [1]

Condition (A.10) requires that the fringe sector holds no excess capacity over the production period. Condition (A.11) implies that the fringe reserve will be exhausted by the end of the time horizon and (A.9) yields the unconstrained shadow price of capital to the fringe sector

(A.13) $$\mu_f(t) = [(\delta + r)/a]e^{-rt}.$$

The equilibrium condition for the fringe sector in each time period is found by combining (A.8) and (A.9) to obtain

(A.14) $$P(t) - C_f'(Q_f(t)) - (\delta + r)/a = \lambda_f e^{rt}.$$

This solution yields the optimal production path and capacity level of the fringe sector defined by

(A.15) $$Q_f^*(t) = Q_f^*[P(t),\delta,\phi_f,\psi_f,r]$$

(A.16) $$K_f^*(t) = K_f^*[P(t),\delta,\phi_f,\psi_f,r]$$

The dominant firm, taking the level of production by the fringe sector in each period as given, can determine the series of residual demand curves it faces in the market. That is, market demand, $Q(P(t))$, less the given fringe production, $Q_f(t)$, equals the dominant firm's residual demand in each time period. The dominant firm, given residual demand, chooses an optimal price path which is

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[1]Assuming that $\ell_f(*)$ is concave in $Q_f(t)$ and $K_f(t)$, the Euler conditions (A.8) - (A.12) are both necessary and sufficient for the maximization of (A.7). See Morton I. Kamien and Nancy L. Schwartz (1981) pp. 37-39.

supported by the level of its sales. The optimal price and capital path chosen by the dominant firm maximizes the present value of its discounted cash flow

$$(A.17)\quad \Pi_d = \int_o^T \{P(t)[Q(P(t)) - Q_f(t)] - C_d(Q(P(t)) - Q_f(t)) - [\delta + r]K_d(t)\}e^{-rt}dt + K_d(0)$$

This discounted cash flow is maximized subject to the constraints that

$$(A.18)\quad P(0) = P_o,\ P(T) = \bar{P}$$

$$(A.19)\quad K_d(0) = \underline{K}_d > 0,\ K_d(T) = 0$$

$$(A.20)\quad Q(P(t)) - Q_f(t) \leq aK_d(t)$$

$$(A.21)\quad \int_o^T \{Q(P(t)) - Q_f(t)\}dt \leq S_d(0)$$

where $Q(P(t))$ is the market demand function with $dQ/dP < 0$. $Q(P(t)) - Q_f(t)$ is the residual demand curve faced by the dominant firm in each time period. In effect, the dominant firm takes as given the production path of the fringe sector and provides the additional output necessary to maintain the price it sets. Formally, the dominant firm seeks to maximize the Lagrangian $\ell_d(P(t),K_d(t),\mu_d,\lambda_d;Q_f(t),\delta,r)$ over all time periods defined by

$$(A.22)\quad \int_o^T \{P(t)[Q(P(t)) - Q_f(t)] - C_d(Q(P(t)) - Q_f(t)) - [\delta + r]K_d(t)\}e^{-rt}dt + K_d(0) + \mu_d(t)\{aK_d(t) - Q(P(t)) + Q_f(t)\} + \lambda_d[S_d(0) - \int_o^T \{Q(P(t)) - Q_f(t)\}dt]$$

The first order conditions for the maximization of (A.22) are

$$\text{(A.23)} \quad \{[P(t) - C_d'(t)]dQ(P(t))/dP(t) + Q(P(t)) - Q_f(t)\}e^{-rt}$$

$$- [\mu_d(t) + \lambda_d]dQ(P(t))/dP(t) = 0$$

$$\text{(A.24)} \quad -(\delta + r)e^{-rt} + \mu_d(t)a = 0$$

$$\text{(A.25)} \quad aK_d - Q(P(t)) + Q_f(t) = 0$$

$$\text{(A.26)} \quad S_d(0) - \int_o^T \{Q(P(t)) - Q_f(t)\}dt = 0$$

$$\text{(A.27)} \quad \mu_d(t),\ \lambda_d > 0.$$

As in the case of the fringe sector, (A.25) requires that the dominant firm holds zero excess capacity and (A.26) implies that its reserve will eventually be exhausted. Combining (A.23) and (A.24) the equilibrium condition for the dominant firm is obtained, requiring that

$$\text{(A.28)} \quad P(t) + \frac{Q(P(t)) - Q_f(t)}{dQ(P(t))/dP(t)} - C_d' - (\delta + r)/a = \lambda_d e^{rt}.$$

Equilibrium for the dominant firm requires that the change in total revenue with respect to a change in price less the marginal production and the constant capital costs is equated to the firm's marginal user cost of the resource in all periods of positive output.

The solution to (A.22) yields the optimal pricing path and capacity level of the dominant firm, given the production path of the fringe sector, defined by

$$\text{(A.29)} \quad P^*(t) = P^*[Q_f(t),\delta,r]$$

$$\text{(A.30)} \quad K_d^*(t) = K_d^*[Q_f(t),\delta,r]$$

where the price chosen can be the monopoly price, the competitive

price, or some price in between.[2]

2. The Model Under Adjustment Constraints

The constraint faced by the fringe sector concerning capital adjustments is assumed to be of the form

(A.31) $$-\psi_f(K_f(t)) - \delta K_f(t) \leq \dot{K}_f(t) \leq \phi_f(K_f(t)) - \delta K_f(t),$$

where ϕ_f is the upper bound on the rate at which new capital can be brought on line and ψ_f is the upper bound on the rate at which capital can be sold off. Both are assumed to be related to the level of the existing capital stock. The more capital firms in the fringe sector command, the easier it is to expand further and the harder it is to dispose of capital; i.e.,

(A.32) $$\psi_f' < 0, \ \phi_f' > 0,$$

where $\psi_f' \equiv d\psi_f/dK_f$, and $\phi_f' \equiv d\phi_f/K_f$, the rate of change of the respective constraints with respect to the existing level of the capital stock.

When the constraint on adjusting capital (A.31) is binding for the fringe sector when increasing, but not when decreasing, the level of capacity, the rate of change of the capital stock is defined by

(A.33) $$\dot{K}_f(t) = \phi_f(K_f(t)) - \delta K_f(t).$$

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[2]Following Stephen W. Salant (1976) and Richard J. Gilbert (1978) it is assumed that once the dominant firm announces the price path (A.29) it will not deviate from it at any date in the future. D. M. G. Newberry suggests that, if it did deviate, the solution to the problem (A.22) can be dynamically inconsistent.

This type of constraint may be comparable to a situation where a new technlogy must be developed in order to exploit a certain type of mineral resource which can then replace the existing technology employed in the extraction of other types of ore. The capital stock available to the fringe sector in any given time period will always be the sum of the initial stock of capital and any additions to this stock over time, that is

$$K_f(\tau) = K_f(0) + \int_0^{\tau} \dot{K}_f(t)dt. \tag{A.34}$$

Condition (A.34) allows the fringe sector to sell as much capital as it desires, however, this possibility is irrelevant as long as the fringe has an insufficient level of capital. That is, while the constraint is binding, the amount of capital on hand in any given time period is defined by

$$K_f(\tau) = K_f(0) + \int_0^{\tau}\{\phi_f(K_f(t)) - \delta K_f(t)\}dt. \tag{A.35}$$

The available capital stock is then equal to the initial capital stock plus any additions to capital made while the constraint is binding. Substituting (A.35) into the capital-output constraint (A.5) yields

$$Q_f(\tau) \leq \alpha[K_f(0) + \int_0^{\tau}\{\phi_f(K_f(t)) - \delta K_f(t)\}dt], \tag{A.36}$$

the constrained capital-output relationship. In all periods for which the constraint on increasing capacity is binding the fringe sector maximizes the Lagrangian $\ell_f^c(Q_f(t), K_f(t), \mu_f^c, \lambda_f^c; P^c(t), \delta, \phi_f, \psi_f, r)$ defined by

$$\text{(A.37)} \quad \int_o^\tau \{P^c(t)Q_f(t) - [\delta + r]K_f(t)\}e^{-rt}dt + K_f(0)$$
$$+ \mu_f^c(t)[a[K_f(0) + \int_o^\tau\{\phi_f(K_f(t)) - \delta K_f(t)\}dt] - Q_f(t)]$$
$$+ \lambda_f^c[S_f^\tau(0) - \int_o^\tau Q_f(t)dt]$$

where, again to focus attention on the difference in the shadow price of capital across sectors, it is assumed that the variable costs of production are zero. τ defines the time period at which the constraint is overcome by the fringe sector. $S_f^\tau(0)$ then, is the amount of the resource stock that must be extracted by the fringe sector before the constraint is no longer binding. The superscript c denotes the values of the term while the constraint on increasing capacity is binding for the fringe sector. $P^c(t)$ then, is the optimal price determined by the dominant firm given the fringe sector's constrained production path. The first order conditions which maximize (A.37) in each time period for the fringe sector are

$$\text{(A.38)} \quad P^c(t)e^{-rt} - \mu_f^c - \lambda_f^c = 0$$

$$\text{(A.39)} \quad -(\delta + r)e^{-rt} + \mu_f^c(t)a[\phi_f' - \delta] = 0$$

$$\text{(A.40)} \quad a[K_f(0) + \int_o^\tau\{\phi_f(K_f(t)) - \delta K_f(t)\}dt] - Q_f(t) = 0$$

$$\text{(A.41)} \quad S_f^\tau(0) - \int_o^\tau Q_f(t)dt = 0$$

$$\text{(A.42)} \quad \mu_f^c(t),\ \lambda_f^c > 0$$

As in the unconstrained case, (A.40) requires that the fringe sector holds no excess capacity and (A.41) implies that the fringe sector will exhaust the required amount of its reserve by the time the constraint is overcome. Equation (A.39) yields the constrained shadow price of capital to the firm

(A.43) $$\mu_f^c(t) = [(\delta + r)/a(\phi_f' - \delta)]e^{-rt}.$$

Equations (A.38) and (A.39) imply that the equilibrium condition for the fringe sector over all time periods while the constraint on increasing capacity is binding is defined by

(A.44) $$P^c(t) = [(\delta + r)/a(\phi_f' - \delta)] + \lambda_f^c e^{rt}.$$

Equation (A.44) implies that the constrained market price of the resource is equal to the constrained shadow price of capital plus the constrained marginal user cost of the resource for the fringe sector in equilibrium.

3. Including Demand Growth

Consider the instance where demand is growing at some constant rate over time, i.e.,

(A.45) $$Q(P,t) = Q(P(t))e^{\eta t}$$

where η is some positive constant equal to the rate of growth in demand. Examination of the fringe sector's maximization problem (A.7) reveals that growth will not affect these firms directly, in that the fringe is motivated solely by the prices offered in the market. On the other hand, market demand enters explicitly into the dominant firm's maximization problem. Incorporating (A.45) into the problem implies that when the constraint on adjusting capacity is nonbinding, the dominant firm seeks to maximize the Lagrangian $\ell_d(P(t),K_d(t),\mu_d,\lambda_d;Q_f(t),\delta,r,\eta)$ over all time periods defined by

$$(A.46) \quad \int_o^T \{P(t)[Q(P(t))e^{\eta t} - Q_f(t)] - C_d(Q(P(t))e^{\eta t} - Q_f(t)) - [\delta + r]K_d(t)\}e^{-rt}dt + K_d(0) + \mu_d(t)\{ \alpha K_d(t) - [Q(P(t))e^{\eta t} - Q_f(t)]\} + \lambda_d[S_d(0) - \int_o^T \{Q(P(t))e^{\eta t} - Q_f(t)\}dt]$$

Solving from the first order conditions for (A.46), which are similar to those obtained for the case of no growth in demand, yields

$$(A.47) \quad P(t) + \frac{Q(P(t))e^{\eta t} - Q_f(t)}{[dQ(P(t))/dP(t)]e^{\eta t}} - C_d' - (\delta + r)/\alpha = \lambda_d e^{rt}.$$

Equation (A.47) gives the dominant firm's equilibrium condition for the case of growth in market demand.

4. Unlimited Resources

A final area of concern is in the case of a dominant firm with such a large resource stock it can treat its reserve as inexhaustible, while the fringe sector is restricted to have a finite deposit. This is simply a special case of the problem presented above where the constraint on total production (A.21) is nonbinding for the dominant firm. The fringe maximization problem would remain unchanged, while the dominant firm would now seek to maximize the Lagrangian $\ell_d(P(t),K_d(t),\mu_d,;Q_f(t),\delta,r)$ over all time periods defined by

$$(A.48) \quad \int_o^T \{P[Q(P(t)) - Q_f(t)] - C_d(Q(P(t)) - Q_f(t)) - [\delta + r]K_d(t)\}e^{-rt}dt + K_d(0) + \mu_d(t)[\alpha K_d(t) - Q(P(t)) + Q_f^*(P(t))]$$

Solving the first-order conditions to (A.48), equilibrium requires

$$\text{(A.49)} \qquad P(t) + \frac{Q(P(t)) - Q_f(t)}{dQ(P(t))/dP(t)} - C_d' - (\delta + r)/a = 0,$$

that is, marginal revenue is equated to the marginal production costs in each time period.

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